US Department
of Transportation

**National Highway
Traffic Safety
Administration**

DOT HS 809428 **June 2002**

Preliminary Findings of the Effect of Tire Inflation Pressure on the Peak and Slide Coefficients of Friction

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. DOT 809428	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Preliminary Findings of the Effect of Tire Inflation Pressure on the Peak and Slide Coefficients of Friction		5. Report Date June 2002
6. Author(s) James D. MacIsaac Jr. & Dr. W. Riley Garrott National Highway Traffic Safety Administration (NHTSA)		7. Performing Organization Code
		8. Performing Organization Report No.
9. Performing Organization Name and Address National Highway Traffic Safety Administration Vehicle Research and Test Center P.O. Box B-37 East Liberty, OH 43319-0337		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 400 Seventh Street, S.W. Washington, D.C. 20590		13. Type of Report and Period Covered Technical report
		14. Sponsoring Agency Code NHTSA/NRD-50

15. Supplementary Notes

The authors acknowledge the support of this effort by: Bill Lyon and Don Bayliss of TRC and the Union County, Ohio Sheriff's Office.

16. Abstract

To assist in assessing the safety benefits of tire pressure monitoring systems, the National Highway Traffic Safety Administration's Vehicle Research and Test Center completed a preliminary investigation into the effects of tire inflation pressure on peak and slide coefficients of friction.

The peak and slide friction coefficients were measured with a precision skid trailer system. Testing followed a series of procedures developed by the American Society for Testing and Materials (ASTM) to determine the peak and slide coefficients of tire-roadway friction. The results of testing with a set of commercially-available, modern all-season radial passenger car tires and ASTM radial test tires (E 1136) are documented in this report. Both tire types were tested over a range of seven speeds and at two or three inflation pressures. While the results from the modern radial tires were the primary focus of this report, the results from the ASTM test tires were included to serve as a reference due to their widespread use by State DOTs and automotive test facilities. The test surface was a section of a rural state route that experiences moderate to heavy traffic (closed for these tests).

The peak coefficient of friction for the ASTM radial tire decreased by an average of 7% on dry asphalt and 6% on wet asphalt as inflation pressure was lowered 51% from 35 to 17 psi (241 to 117 kPa). For the modern radial passenger car tire, the peak coefficient decreased by 3% on dry asphalt for the 51% reduction in pressure. However, the modern radial tire yielded opposite results when wet, with its wet peak coefficient increasing by an average of 4% when inflation pressure was decreased by 51%.

The slide coefficients of friction for both the modern radial tires (tested both wet and dry) and the ASTM radial (only tested wet) showed little or no influence of inflation pressure. The average slide coefficients of friction varied by no more than 1.5% as the inflation pressure was lowered from 35 to 17 psi (241 to 117 kPa).

With the exception of the wet peak results for the modern radial tire, the results of the current study follow the same trends as independent tests published by Collier and Warchol of the B.F. Goodrich Co. in 1980. Comparisons with similar tests performed by the Goodyear Tire & Rubber Company are also included.

Overall, these tests were meant to be a preliminary examination of the effects of tire underinflation. It was determined that the tire model, amount of tread wear, and water depth may significantly influence tire-road friction results. Recommendations for future tire-road friction tests include using multiple tire models, using new tires for each test series, and carefully regulating water depth.

17. Key Words effects of tire pressure, inflation pressure, coefficient of friction, TPMS, peak, slide, underinflation, TREAD Act.		18. Distribution Statement Document is available to the public from the National Technical Information Service Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9 (Celsius) - 32°C	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

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EXECUTIVE SUMMARY

To assist the National Highway Traffic Safety Administration (NHTSA) in assessing the safety benefits of tire pressure monitoring systems, NHTSA's Vehicle Research and Test Center (VRTC) completed a preliminary investigation into the effects of tire inflation pressure on peak and slide coefficients of friction. Though both coefficients are known to vary substantially with speed and tire/roadway conditions (especially wet versus dry roadways), less is known of the effects of tire inflation pressure on the friction coefficients.

In June 2001 a series of tests were undertaken to measure the peak and slide coefficients of friction, wet and dry, on a section of a rural state route that experiences moderate to heavy traffic (closed for this testing). The peak and slide friction coefficients were determined with a precision skid trailer system, which consists of a heavily modified pickup truck towing a fully instrumented skid trailer. Testing followed a series of procedures developed by the American Society for Testing and Materials (ASTM) to determine the peak and slide coefficients of tire-roadway friction. Two types of tires were used in testing: Commercially-available, all-season radial passenger car tires and ASTM radial "Standard Reference Test Tires" (SRTT). The tires were tested over a range of seven speeds and two or three inflation pressures. Results from the commercially-available radial tires are the primary focus of this report, with the results from the SRTT tires being used to establish a baseline reference.

The peak coefficient of friction for the SRTT decreased by an average of 7 percent dry and 6 percent wet as inflation pressure was lowered from 35 to 17 psi (241 to 117 kPa). For the commercially-available passenger car radial tire, the peak coefficient decreased by 3 percent dry over the same pressure range. However, the commercially-available passenger car radial tire yielded opposite results when wet, with its wet peak coefficient increasing by an average of 4 percent as inflation pressure was decreased.

The slide coefficients of friction for both the SRTT (only tested wet) and the commercially-available passenger car radial tires (tested both wet and dry) showed little or no influence of inflation pressure. The average slide coefficients of friction varied no more than 1.5 percent as

the inflation pressure was lowered from 35 to 17 psi (241 to 117 kPa). The average changes in the slide coefficients of friction were well below their standard deviations.

With the exception of the wet peak results for the commercially-available passenger car radial tire, the results of VRTC's skid tests follow the same trends as independent tests published by Collier and Warchol in 1980.

It is difficult to draw conclusions from tests of one commercially-available passenger car radial tire model and a 1980's era ASTM radial test tire. The limited numbers of tires available for testing meant that significant tread wear occurred during the dry tests, which may have affected the results of dry tests. Differences in results between the two tires may be attributed to the SRTT's older design and tire compounding, circa 1986, and that the passenger car tire had an aspect ratio of 60 compared to 75 for the SRTT.

The findings of these preliminary tests warrant a more thorough investigation into the effects of inflation pressure on the coefficients of friction. Future tests should include more tires and use new, uniformly prepared tires for each test condition to eliminate the influences of tread wear. Also, because of the length of time each test sequence requires, test speeds should be randomized to help counteract the temperature bias that occurs during daytime testing.

1.0 INTRODUCTION

To assist the National Highway Traffic Safety Administration (NHTSA) in assessing the safety benefits of tire pressure monitoring systems, the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VRTC) conducted a preliminary investigation into the effects of tire inflation pressure on the peak and slide coefficients of tire-road friction in June of 2001. Though both coefficients are known to vary substantially with speed and tire/roadway conditions (especially wet versus dry roadways), less is known of the effects of tire inflation pressure on the friction coefficients. The results of this investigation are contained in this report. Information on the related topic of the effects of tire inflation pressure on vehicle stopping distance can be found in the companion report ***Preliminary Investigation Into the Effect of Tire Inflation Pressure on Stopping Distance*** [1].

2.0 TEST METHOD

The peak and slide coefficients of friction were measured for wet and dry conditions using two types of radial tires. The tests were conducted at multiple inflation pressures and speeds. The road surface was a section of a rural state route (Ohio State Route 347) that experiences moderate to heavy traffic. This stretch of road, closed for these tests, was last paved in 1994 with Ohio DOT 446 asphalt material and had a dry ASTM[1] E 274 skid number of 83[2]. A precision skid truck (with trailer), built to ASTM specifications, was used to measure the relative coefficient of friction between each tire and the State Route 347 asphalt.

Table 2.1: Test Tire Specifications

Tire	Size	Type	Tread Depth New
ASTM E 1136 (SRTT)	P195/75 R14	Radial	9.3 mm (0.365 in)
Goodyear Eagle LS, All-Season High Performance Touring Radials (OE, TPC - 1089MS)	P225/60 R16	Radial	7.8 mm (0.305 in)

Prior to testing, the peak coefficient of friction (Peak Braking Coefficient) was measured using ASTM E 1136 (Figure 2.1) tire in accordance with the ASTM E 1337-90 test method. The slide coefficient of friction (Skid Number) was measured using ASTM E 501 (Figure 2.1) tire in accordance with the ASTM E 274-90 test method.

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[1] ASTM is the American Society For Testing and Materials, 100 Barr Harbor Drive
West Conshohocken, Pennsylvania, USA 19428-2959 Phone: (610) 832-9585 Fax: (610) 832-9555

[2] A Skid Number of 83 corresponds to a dry slide coefficient of friction of 0.83 times 100. According to the "Fundamentals of Vehicle Dynamics", T. Gillespie most clean, dry roads have a Skid Number close to 81.

Figure 2.1: ASTM 1136 SRTT Radial, ASTM 501 Bias Belted, Goodyear Eagle LS Radial

Figure 2.1 displays the three types of tires used for the traction trailer tests. The ASTM 1136"SRTT" Tire is a radial tire with a normal, but dated, all-season tire tread. The ASTM 501 tire is a bias-belted tire that has only circumferential tread grooves that form solid rings of tread unbroken by any perpendicular tread grooves. The Goodyear Eagle LS tire has is a commercially-available radial tire with a modern all-season tread design.

The main focus of the testing, the set of original equipment, P225/60 R16 Goodyear Eagle LS all-season passenger car radial tires, had about 2000 miles of use on them (on the same vehicle) at the beginning of testing. This size tire (P225/60 R16) is the fifth most popular size for original equipment passenger car tires[3]. These tires, which were used in similar tests on an ABS-equipped vehicle, were sufficiently worn in to no longer be considered new and had about 75 percent of their original tread depth. It was thought that the use of these tires would yield results more representative of an average tire in use on US roadways.

The ASTM tires were broken in, per ASTM test procedures, for a minimum of 200 miles before use. Both the SRTT and Goodyear Eagle LS tires were tested down to a tread depth of 2/32 of

[3]The P225/60 R16 size tire was original equipment on 4.1% of passenger car vehicles. The most popular size, P235/75 R15, was original equipment on 7.1% of passenger car vehicles. Since the top 10 most popular original equipment sizes only account for 43.1% of original equipment tires, O.E. tire fitments are quite varied. Source: Rubber Manufacturers Association.

an inch (new is 10-12 / 32). To conserve the Eagle tires, the peak coefficients were taken from the E 274 slide procedure. While ASTM has a separate peak procedure in which the tires are only locked long enough to "chirp", the slide procedure takes a peak reading and then holds the wheels locked to determine the slide coefficient. This method yielded sufficiently accurate values and conserved the tires.

The test loads for each tire are listed in Table 2.2. The ASTM tires were tested at the load specified by the corresponding ASTM test procedure. The Eagle P 225/60 R16 was tested at 75 percent of The Tire and Rim Association's (T&RA) tire load limit for an inflation pressure of 35 psi (241 kPa)[4]. These loads were maintained throughout testing.

Table 2.2: Tire Test Loads

Tire	**Test Load**	**Rationale**
ASTM E 1136	1031 lbf (4586 N)	ASTM E 1137
Goodyear Eagle LS	1205 lbf (5360 N)	75% of T&RA Load @ 35 psi (240 kPa)

Wet tests were done first to conserve tire tread. The ASTM tires were tested using the ASTM specified water application rate from the skid truck system. Eagle tires were too wide for the skid truck's ASTM water application heads (see Figure 2.3) and required a separate water truck to wet the surface during the wet tests. Though the water application rates were different between the ASTM and Eagle tires, rates were kept constant for each tire throughout its test sequence. Conventional ASTM peak and slide numbers were taken using both water application methods to explore the effects of these different water depths.

Test speeds were varied from 10-70 mph in 10 mph increments. The sequences of the test speeds are listed in Table 2.3. Since tests at the high speeds wear away tread faster, the Eagle tires were tested from the slowest to fastest speed to conserve tread. Test pressures for the Eagle tires were 35, 24, and 17 psi. The radial SRTT (E 1136) tires were tested at 17 psi and 35 psi (241 kPa).

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[4] Tire load limits are listed in the Tire and Rim Association's 2001 Year Book (www.us-tra.org).

Table 2.3: Test Speed Sequence

Test	Conditions	ASTM Tires Test Speed Sequence (mph)	Eagle Tires Test Speed Sequence (mph)
Peak	Wet & Dry	70, 10, 20, 30, 40, 50, 60	10, 20, 30, 40, 50, 60, 70 *
Slide	Wet & Dry	40, 10, 20, 30, 70, 50, 60	10, 20, 30, 40, 50, 60, 70

*Peak dry for the OE tire was obtained from the slide dry numbers due to concerns over inducing excessive tire wear if used in both dry procedures.

The skid truck, pictured in Figure 2.3, consists of a heavily modified full-sized pickup truck that houses the instrumentation and water application equipment. The tires are mounted on a "skid trailer" that is towed behind the truck. The skid trailer is equipped with water application nozzles and electronically controlled brakes that can be applied for various durations depending on the test. The skid trailer's axles are instrumented with load cells to measure the horizontal braking and normal forces in real time, which are then sent to the truck for data logging. The particular skid truck used for these tests is located at the Transportation Research Center in East Liberty Ohio and is used annually by multiple state DOTs to calibrate their own skid measurements trucks.

Figure 2.2: Transportation Research Center Inc. Skid Truck System

Figure 2.2 displays a view of the complete TRC Skid Truck System. The system consists of a late model full-sized pickup truck towing a single-axle traction trailer.

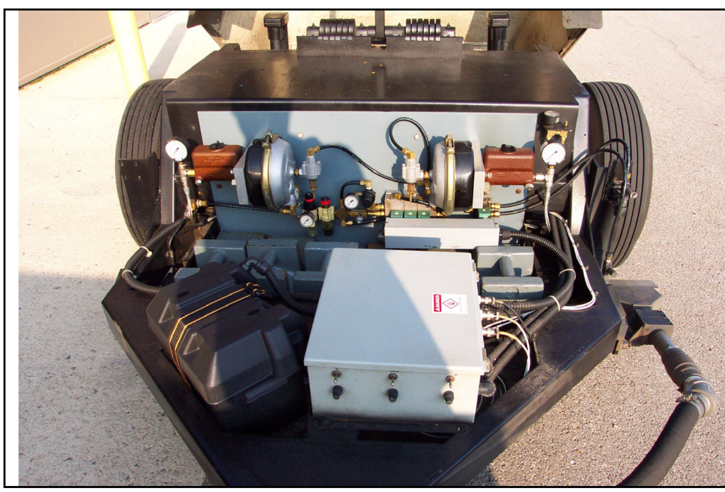

Figure 2.3: TRC. Skid Trailer, Water Application Nozzle, and Data Acquisition System

Figure 2.3 displays close-up views of the instrumentation and components of the TRC Skid Truck system that were mentioned in the figure title.

3.0 RESULTS

Peak and slide coefficients of friction, taken at ASTM specified inflation pressures, with the ASTM specified tires and speeds, were measured prior to testing in order to categorize the road surface. These measured values follow in Table 3.1.

Table 3.1: State Route OH 347 ASTM Surface Coefficients

Coefficient	Surface Condition	Average Coefficient	Samples
Peak	Wet – skid truck water application (ASTM)	0.87	5
Peak	Wet – water truck water application*	0.86	5
Peak	Dry	1.01	5
Slide	Wet – skid truck water application (ASTM)	0.63	7
Slide	Wet – water truck water application*	0.55	7
Slide	Dry	0.83	7

*Necessary since wet tests with Eagle tires were done on a surface wetted by a water truck instead of the skid trailer, which may have led to a different water depth.

The dry slide coefficient of 0.83 yields a Skid Number of 83. As was previously stated, this is typical for a clean dry road. The differing water application methods between the ASTM tires and the passenger car radial tires had little effect on the average wet peak coefficient of friction, changing by 0.01 or about 1.2 percent. The average wet slide coefficient decreased by 0.08 or 12.7 percent, which would indicate that the water application method affected the slide coefficient of friction.

The ASTM water application method is preferable, since it applies water to the surface immediately before the tire passes over the area. The rate of water application by the skid truck is referenced to speed to help assure the same water depth regardless of test speed. In comparison, the water truck runs at one speed (20 mph / 32 kph) and completely wets the entire test surface as it makes a pass. Since the water truck must leave the test surface before the skid truck can make a run, the water depth may vary due to evaporation or non-uniform drainage that occurs by the time the skid truck has a chance to complete its pass.

Future tests should include water nozzles on the skid trailer that are wide enough to accommodate wider tires. The water application rate of the skid truck would also have to be adjusted to maintain the same water depth over a wider surface area.

3.1 Peak Coefficient of Friction

The peak coefficient of friction was determined on SR 347 in both wet and dry surface conditions. Seven different test speeds were used for each inflation pressure. The SRTT tires were tested at 35 and 17 psi (241 and 117 kPa) and the Eagle tires were tested at 35, 24, and 17 psi (241, 165, 117 kPa). Each peak number is the average of 5 samples with any outliers removed, per ASTM procedures, before averaging. Peak numbers are generated by the progressive application of the skid trailer brakes until the wheel locks and a "chirp" is generated. On dry surfaces, these chirps can lead to significant tire wear. Tests were terminated when the allowable tire wear was exceeded. The wet and dry peak coefficients of friction were measured from June 7 through June 14, 2001 on days with no accumulated precipitation on the road surface.

3.1.1 Wet Peak Coefficient of Friction

The results of wet peak coefficients for the SRTT and Eagle tire are contained in Table 3.2 and Table 3.3. The SRTT tires were tested with the standard ASTM water application method, while the Eagle tires were tested with a water truck wetting the surface.

Table 3.2: Wet Peak Coefficients of Friction from State Route OH 347

Tire / Inflation Pressure		SRTT	SRTT	EAGLE	EAGLE	EAGLE
Speed mph	Speed kph	35 psi (241 kPa)	17 psi (117 kPa)	35 psi (241 kPa)	24 psi (165 kPa)	17 psi (117 kPa)
10	**16**	0.94	0.91	0.89	0.93	0.94
20	**32**	0.95	0.87	0.91	0.98	0.94
30	**48**	0.90	0.88	0.90	0.92	0.94
40	**64**	0.87	0.83	0.91	0.93	0.91
50	**80**	0.87	0.81	0.86	0.89	0.90
60	**97**	0.86	0.77	0.86	0.86	0.89
70	**113**	0.82	0.76	0.85	0.87	*

*Test terminated when allowable tire wear was exceeded

Table 3.3: Percent Change in the Wet Peak Coefficient of Friction between Pressures

Tire / Inflation Pressure		SRTT	EAGLE	EAGLE	EAGLE
Speed (mph)	Speed (kph)	35 / 17 psi (241 /117 kPa)	35 / 24 psi (241 / 165 kPa)	35 / 17 psi (241 / 117 kPa)	24 / 17 psi (165 / 117 kPa)
10	**16**	-3.2%	4.5%	5.6%	1.1%
20	**32**	-8.4%	7.7%	3.3%	-4.1%
30	**48**	-2.2%	2.2%	4.4%	2.2%
40	**64**	-4.6%	2.2%	0.0%	-2.2%
50	**80**	-6.9%	3.5%	4.7%	1.1%
60	**97**	-10.5%	0.0%	3.5%	3.5%
70	**113**	-7.3%	2.4%	*	*
Average		-6.2%	3.2%	3.6%	0.3%
Standard Deviation		1.2%	1.6%	3.0%	1.3%

*Test terminated when allowable tire wear was exceeded

On wet asphalt, the SRTT average (5 samples) measured peak coefficient of friction dropped as much 10.5 percent and as little as 2.2 percent when the inflation pressure was halved. The magnitude of these fluctuations did not show a trend of speed dependence. The largest decrease in the average wet peak coefficient occurred at 60 mph (97 kph), the smallest decrease at 30 mph (48 kph). Over the range of 7 speeds, the average decrease in the peak friction value when inflation pressure was dropped from 35 psi (241 kPa) to 17 psi (117 kPa) was 6.2 percent. The results from the SRTT tire's wet peak coefficients of friction verse inflation pressure are plotted in Figure 3.1 for the seven test speeds.

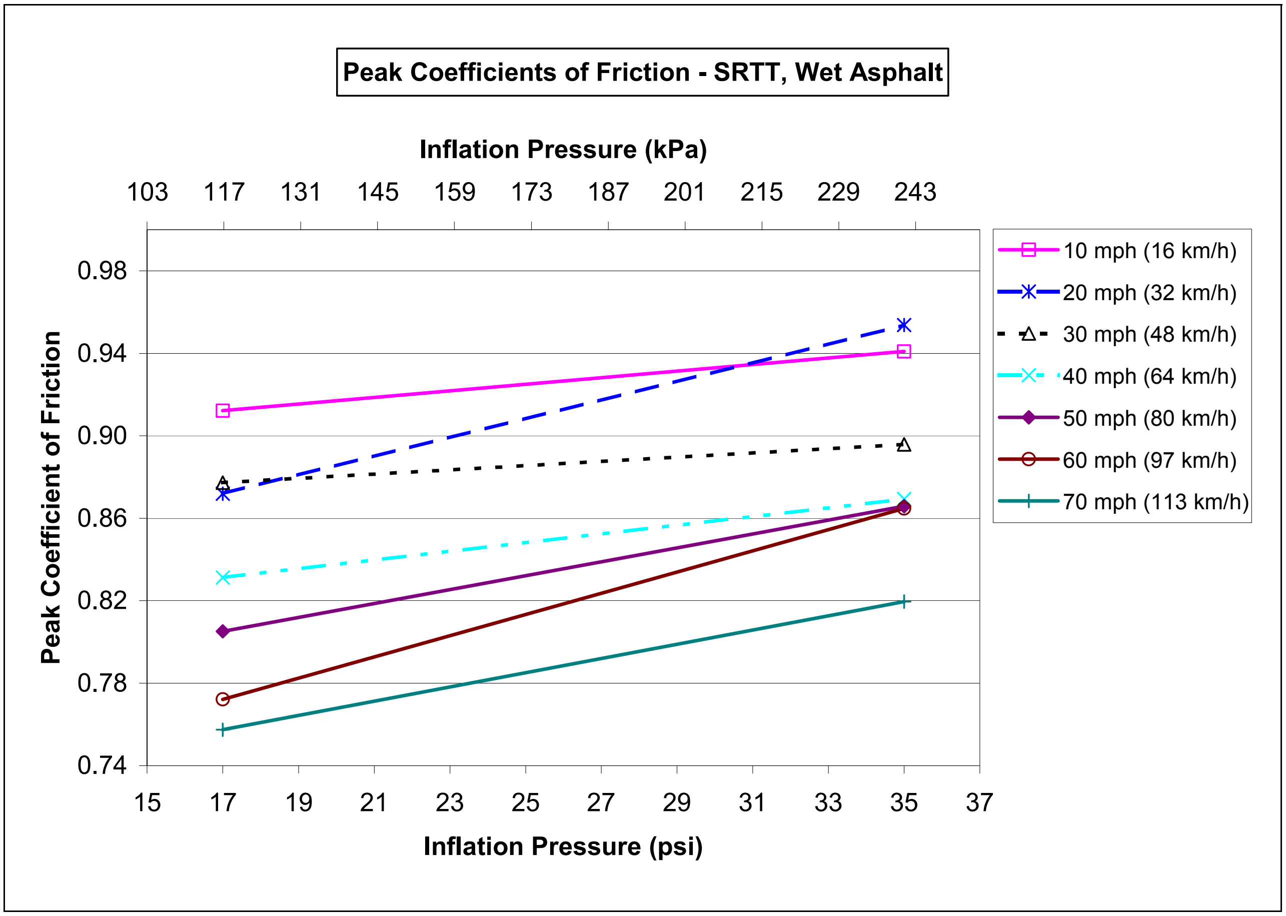

Figure 3.1: SRTT Tire - Wet Peak Coefficient of Friction vs. Inflation Pressure

Figure 3.1 displays the trends of the peak friction coefficient versus inflation pressure as measured on wet asphalt with the SRTT Tire. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features peak coefficients of friction with a scale that ranges from 0.74 to 0.98. Average values of the peak coefficients were measured for two inflation pressures, 17 psi (117 kPa) and 35 psi (241 kPa). For each of the seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments, the two data points are connected by lines. For all seven test speeds plotted, the average peak coefficient was noticeably lower at the 17 psi (117 kPa) than at 35 psi (241 kPa). The numerical data for this figure is located in Table 3.2.

Figure 3.1 illustrates the strong influence of inflation pressure on the wet peak coefficient of friction for the SRTT tire. It is important to note however that the results for the SRTT tire represent more than a 50% drop in inflation pressure, which is an extreme case. Also, it is important to mention that the lines plotted in Figure 3.1 (SRTT tire) between the coefficients measured at 17 and 35 psi (117 and 241 kPa) do not necessarily represent the coefficients for intermediate pressures. For instance, the data in following graphs from the Eagle tire, which includes an additional test pressure of 24 psi (165 kPa), has widely varying results at the intermediate pressure. This suggests that effect of inflation pressure on the amount of tire-road friction does not follow a simple linear relationship.

Figure 3.2 plots the same wet peak coefficients for the SRTT tire against test speed. The normal trend, which is what this Figure 3.2 follows, is for the both peak and slide coefficients of friction to decrease with increasing speed.

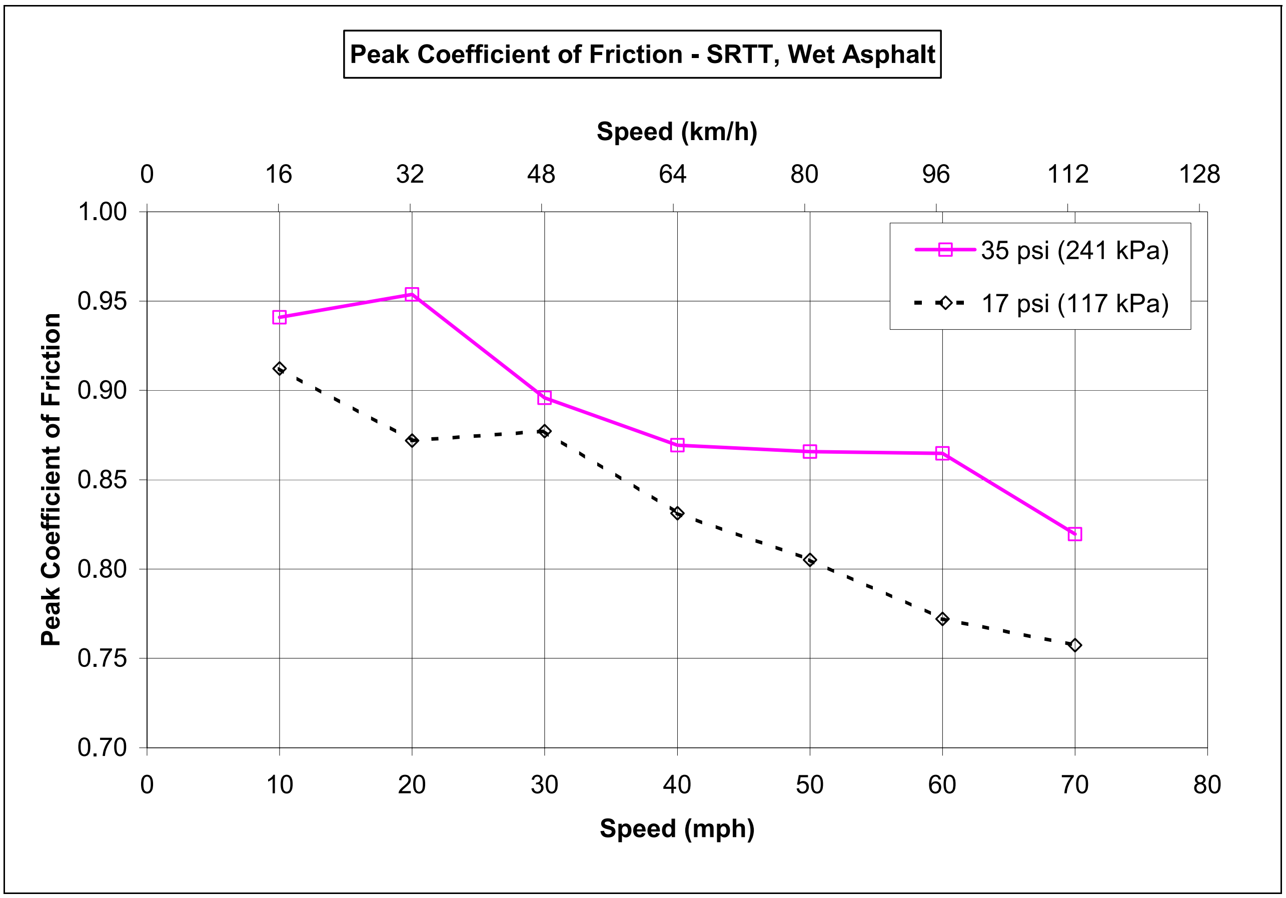

Figure 3.2: SRTT Tire - Wet Peak Friction Coefficients vs. Speed

Figure 3.2 displays the trends of the peak friction coefficient versus test speed as measured on wet asphalt with the SRTT Tire. The x-axis features test speed with a scale that ranges from 0 to 80 mph (0 to 129 kph). The y-axis features peak coefficients of friction with a scale that ranges from 0.70 to 1.00. Average values of the peak coefficients were measured at seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments. The seven data points for each inflation pressure are connected by an incremental point-by-point line, *rather than a curve fit. For all seven test speeds plotted, the average peak coefficient was noticeably lower at the 17 psi (117 kPa) than at 35 psi (241 kPa). The numerical data for this figure is located in Table 3.2.*

As with Figure 3.1, Figure 3.2 illustrates a strong influence of inflation pressure on the SRTT tire for all seven test speeds.

The results of the wet peak coefficients verse inflation pressure for the Eagle tires are plotted in Figure 3.3. Figure 3.4 documents the wet peak coefficients with the Eagle tires verse the initial test speed.

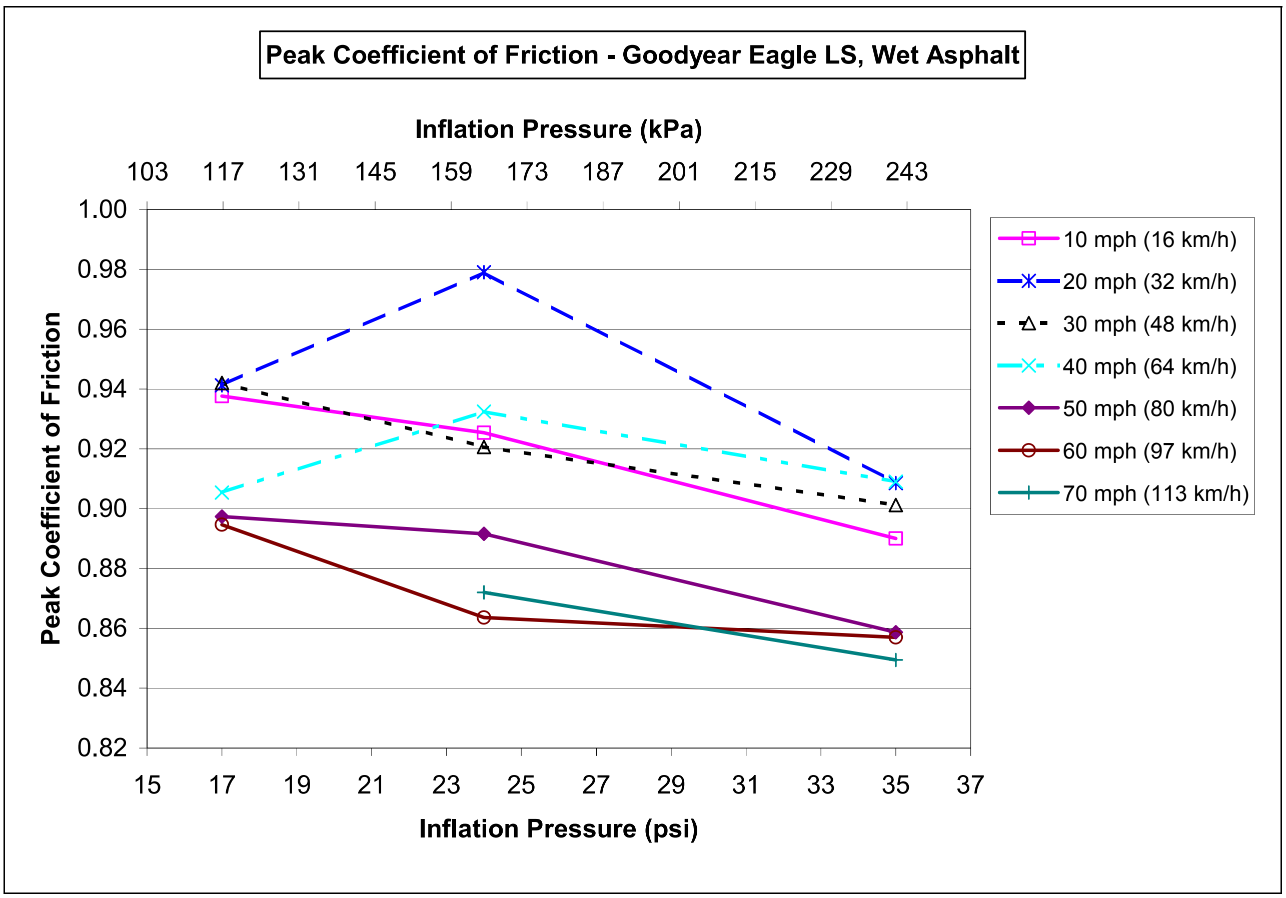

Figure 3.3: Eagle Tire - Wet Peak Friction Coefficients vs. Inflation Pressure

Figure 3.3 displays the trends of the peak friction coefficient versus inflation pressure as measured on wet asphalt with the Goodyear Eagle LS tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features peak coefficients of friction with a scale that ranges from 0.82 to 1.00. Average values of the peak coefficients were measured for three inflation pressures: 17 psi (117 kPa), 24 psi (165 kPa), and

35 psi (241 kPa). For each of the seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments, the three data points are connected by an incremental point-by-point line. The Eagle tires had higher wet peak coefficients of friction over the for six of the seven test speeds (40 mph is the exception) when at 24 and 17 psi (165 and 117 kPa) than when properly inflated to 35 psi (241 kPa). The numerical data for this figure is located in Table 3.2.

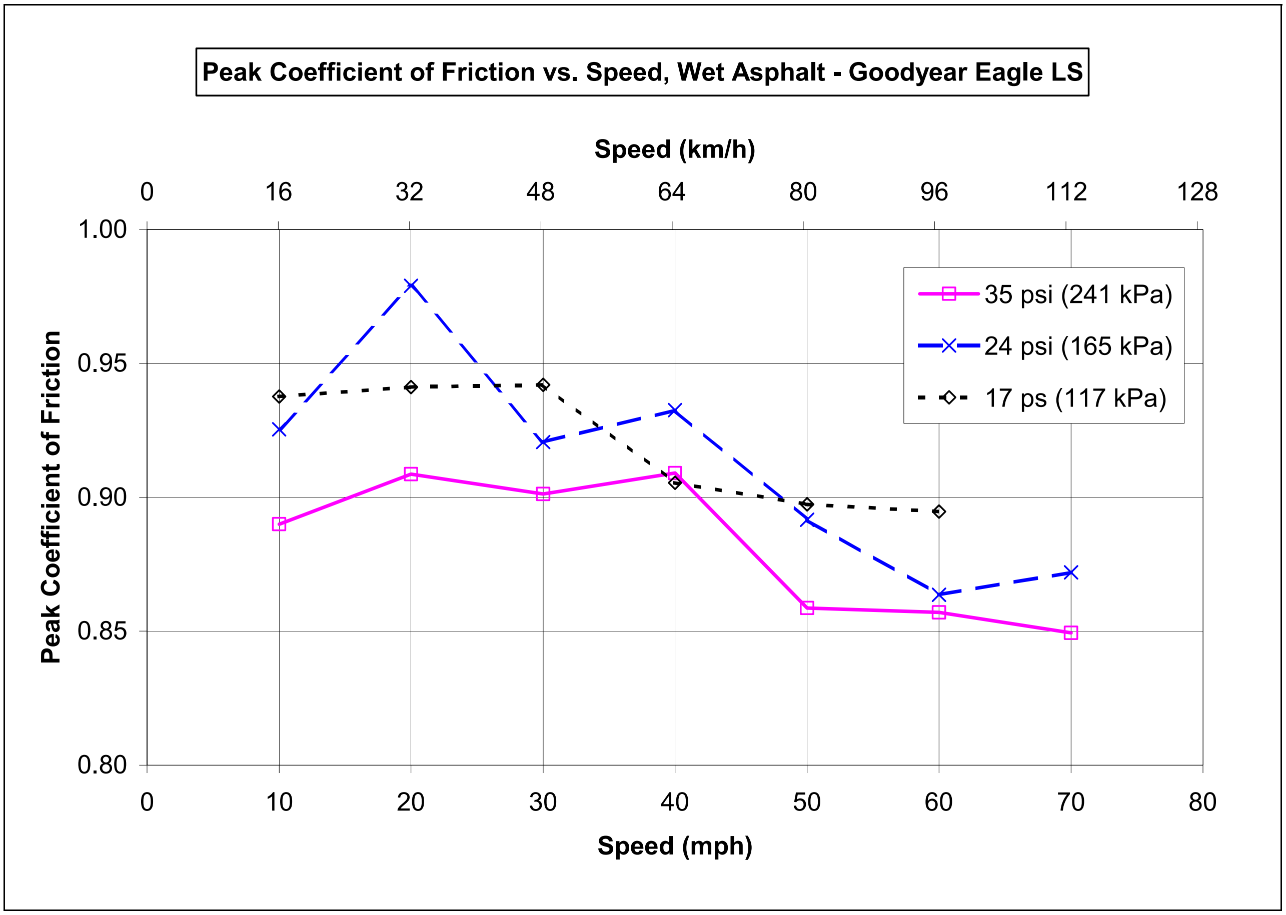

Figure 3.4: Eagle Tire - Wet Peak Friction Coefficients vs. Speed

Figure 3.4 displays the trends of the peak friction coefficient versus test speed as measured on wet asphalt with the Goodyear Eagle LS tire. The x-axis features test speed with a scale that ranges from 0 to 80 mph (0 to 129 kph). The y-axis features peak coefficients of friction with a scale that ranges from 0.80 to 1.00. Average values of the peak coefficients were measured at seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments. The seven data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. Over the range of test speeds, the average peak coefficient was noticeably lower at the 35 psi (241 kPa) than for 17 and 24 psi (117 and 165 kPa). The only exception was at 40 mph, where the coefficient at 17 psi (117kPa) was slightly lower than the coefficient at 35 psi (241 kPa). The numerical data for this figure is located in Table 3.2.

In contrast to the SRTT tires, the Eagle tires had higher wet peak coefficients of friction over the for six of the seven test speeds (40 mph is the exception) when at 24 and 17 psi (165 and 117 kPa) than when properly inflated to 35 psi (241 kPa). While the trend of higher wet peak coefficients at lower inflation pressures may be surprising, with five samples taken at each condition, the data is well supported.

As seen in Figure 3.3, the wet peak friction coefficient increases as inflation pressure is dropped from 35 to 24 psi (241 to 165 kPa) and for some speeds continues to increase when pressure was dropped from 24 to 17 psi (165 to 117 kPa). The exception to the increase was at 20 and 40 mph (32 and 64 kph), during which the wet peak coefficients dropped sharply from 24 to 17 psi (165 to 117 kPa). These decreases in the coefficients represented only a 2 to 4% reduction, and their final values are not lower than their values at 35 psi (241 kPa).

The wet peak coefficients for the 8.86 inch wide, 5.31 inch tall (225 x 135 mm) Eagle tire exhibited trends that were opposite to those of the 7.68 inch wide, 5.75 inch tall (195 x 146 mm) SRTT tire. It is unknown whether or not the differences in trends can be attributed to the short/wide profile of the Eagle tire versus the tall/narrow profile of the SRTT tire or other factors. One factor, water application with the water truck instead of the traction trailer's water application system may have influenced this data. However, tread wear should not have been an issue since the wet peak tests were the first tests to be completed for each tire.

3.1.2 Dry Peak Coefficient of Friction

Table 3.4 and Table 3.5 contain the results of dry peak coefficient measurements taken with the SRTT and the Eagle tires. A number of tests with the Eagle tires were terminated when the tread wear exceeded allowable limits. The tread wear that occurred during these dry tests may have affected the results of dry tests.[5] How much of an effect tread wear had on the results is not known.

Table 3.4: Dry Peak Coefficients of Friction from State Route OH 347

Tire / Inflation Pressure		SRTT	SRTT	EAGLE	EAGLE	EAGLE
Speed (mph)	**Speed (kph)**	**35 psi (241 kPa)**	**17 psi (117 kPa)**	**35 psi (241 kPa)**	**24 psi (165 kPa)**	**17 psi (117 kPa)**
10	**16**	1.10	1.03	1.08	1.10	1.08
20	**32**	1.08	–	1.09	1.09	1.06
30	**48**	1.05	0.98	1.07	1.06	1.01
40	**64**	1.01	0.95	1.06	1.04	1.00
50	**80**	0.98	0.92	1.06	*	1.00
60	**97**	0.99	0.90	0.98	*	0.99
70	**113**	0.95	0.88	*	*	*

*Test terminated when allowable tire wear was exceeded, – Outlier

Table 3.5: Percent Change in the Dry Peak Coefficient of Friction between Pressures

Tire / Inflation Pressure		SRTT	EAGLE	EAGLE	EAGLE
Speed (mph)	**Speed (kph)**	**35 / 17 psi (241 /117 kPa)**	**35 / 24 psi (241 / 165 kPa)**	**35 / 17 psi (241 / 117 kPa)**	**24 / 17 psi (165 / 117 kPa)**
10	**16**	-6.4%	1.9%	0.0%	-1.8%
20	**32**	–	0.0%	-2.8%	-2.8%
30	**48**	-6.7%	-0.9%	-5.6%	-4.7%
40	**64**	-6.0%	-1.9%	-5.7%	-3.9%
50	**80**	-6.1%	*	-5.7%	*
60	**97**	-9.1%	*	1.0%	*
70	**113**	-7.4%	*	*	*
Average		-6.9%	-0.2%	-3.1%	-3.3%
Standard Deviation		3.0%	2.4%	2.0%	2.8%

*Test terminated when allowable tire wear was exceeded, – Outlier

Figure 3.6 shows the dry peak coefficients for the SRTT tires plotted against inflation pressure.

[5] Literature suggests that tread wear can have a large effect on the coefficients of friction. For instance, a tire tread worn 90 percent can decrease the peak coefficient of friction by 15 percent on totally dry surfaces and up to 50 percent on wet surfaces [2].

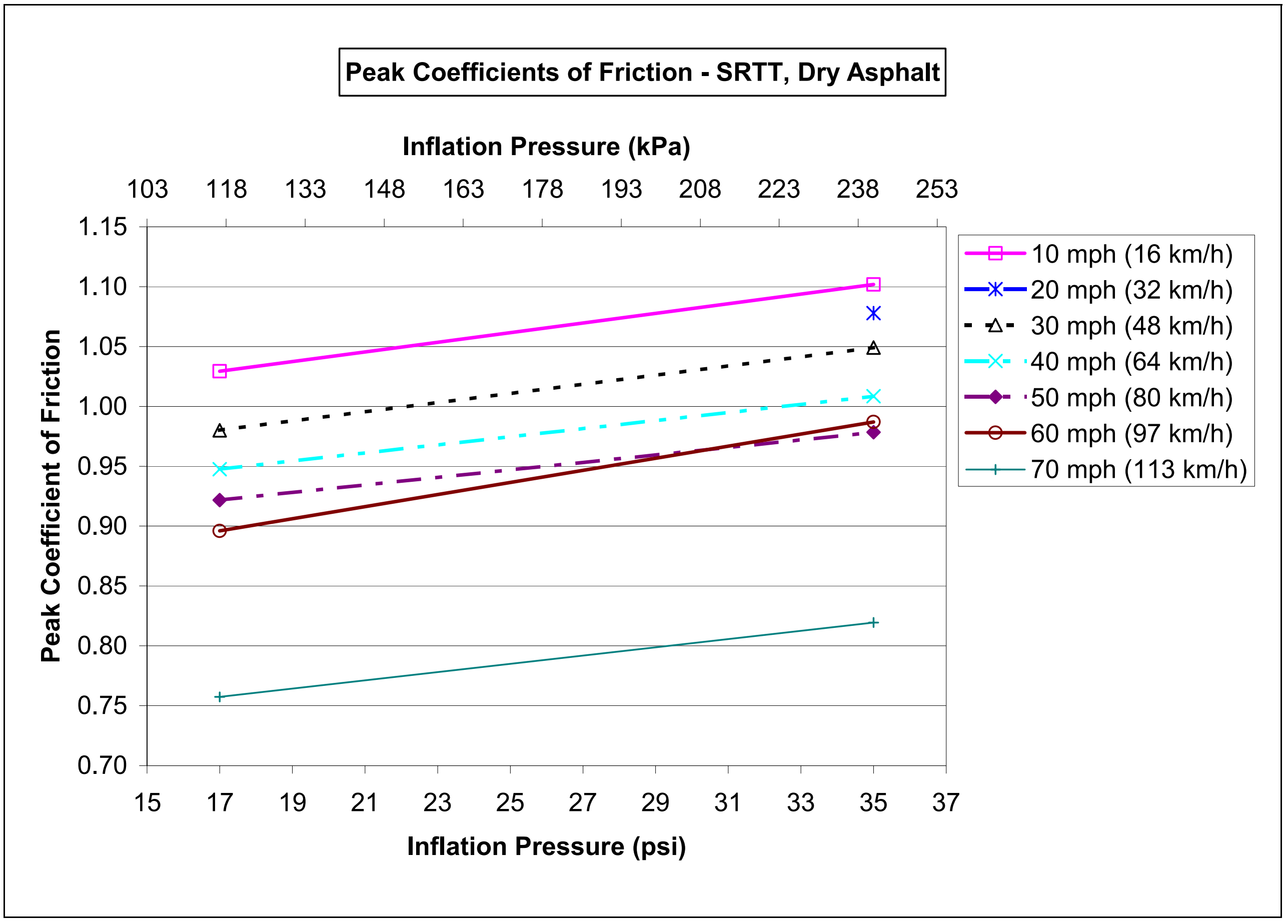

Figure 3.5: SRTT Tire - Dry Peak Friction Coefficients vs. Inflation Pressure

Figure 3.5 displays the trends of the peak friction coefficient versus inflation pressure as measured on dry asphalt with the SRTT tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features peak coefficients of friction with a scale that ranges from 0.70 to 1.15. Average values of the peak coefficients were measured for two inflation pressures: 17 psi (117 kPa) and 35 psi (241 kPa). For each of the seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments, the two data points are connected by a line. For all seven test speeds plotted, the average peak coefficient was noticeably lower at the 17 psi (117 kPa) than at 35 psi (241 kPa). The numerical data for this figure is located in Table 3.4.

Similar to its wet peak trends, the dry peak coefficients for the SRTT tires drop up to 9% as inflation pressure is reduced from 35 to 17 psi (241 to117 kPa). The dry peak coefficients are plotted against speed in Figure 3.6.

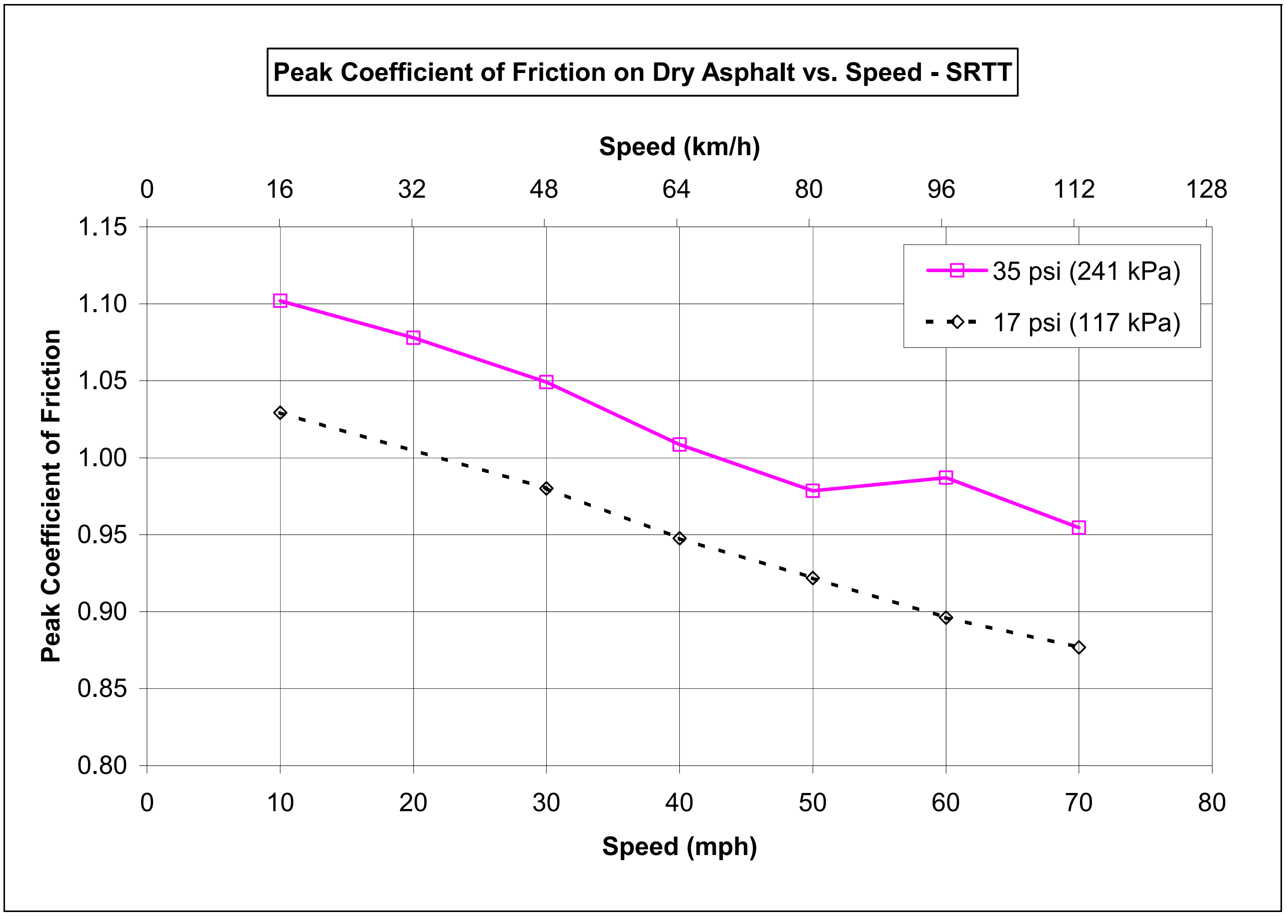

Figure 3.6: SRTT Tire - Dry Peak Friction Coefficients vs. Speed

Figure 3.6 displays the trends of the peak friction coefficient versus test speed as measured on dry asphalt with the SRTT Tire. The x-axis features test speed with a scale that ranges from 0 to 80 mph (0 to 129 kph). The y-axis features peak coefficients of friction with a scale that ranges from 0.80 to 1.15. Average values of the peak coefficients were measured at seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments. The seven data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. For all seven test speeds plotted, the average peak coefficient was noticeably lower at the 17 psi (117 kPa) than at 35 psi (241 kPa). The numerical data for this figure is located in Table 3.4.

For the dry condition, the SRTT tire once again shows a marked decrease in the average peak coefficient of friction across all seven speeds when the recommended inflation pressure is halved. The peak coefficient dropped an average of 7% over the range of speeds.

Figure 3.8 plots the coefficient of friction against inflation pressure and speed for the Eagle tire on dry asphalt.

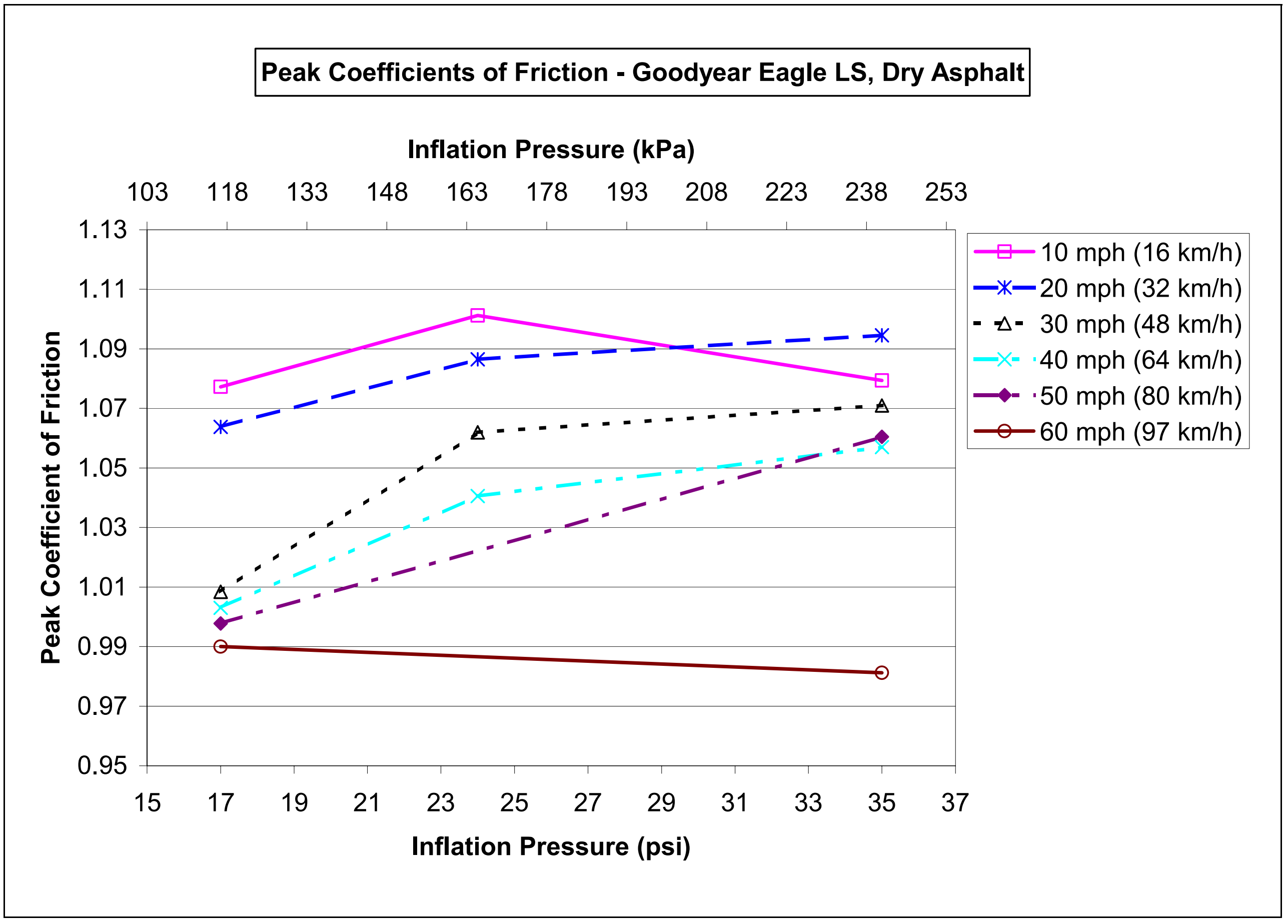

Figure 3.7: Eagle Tire - Dry Peak Friction Coefficients vs. Inflation Pressure

Figure 3.7 displays the trends of the peak friction coefficient versus inflation pressure as measured on dry asphalt with the Goodyear Eagle LS tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features peak coefficients of friction with a scale that ranges from 0.95 to 1.13. Average values of the peak coefficients were measured for three inflation pressures: 17 psi (117 kPa), 24 psi (165 kPa), and 35 psi (241 kPa). For each of the six test speeds, which ranged from 10 to 60 mph (16 to 97 km/h) in 10 mph (16km/h) increments, the three data points are connected by an incremental point-by-point line. At 10 mph (16km/h) the peak coefficient initially increased when inflation pressure was dropped from 35 to 24 psi (241 to 165 kPa), then decreased to the original value as inflation pressure was dropped from 24 to 17 psi (165 to 117 kPa). In the 20 to 50 mph (32 to 80 kph) range , the peak coefficients decreased as inflation pressure decreased. At 60 mph, the peak coefficient increased slightly as inflation pressure was dropped from 35 to 17 psi (241 to 117 kPa). The numerical data for this figure is located in Table 3.4.

The dry peak coefficients for the Eagle tires decrease in the 20 to 50 mph (32 to 80 kph) range when inflation pressure is decreased. The results of runs at 10 and 60 mph (16 and 97 kph) have mixed results. It is important to note that during the 24 psi (165 kPa) trials, the tire wear became so severe that the tests were halted before the 50 and 60 mph test speeds were completed. Therefore, the midrange (24 psi [165 kPa]) response at these two speeds is not known.

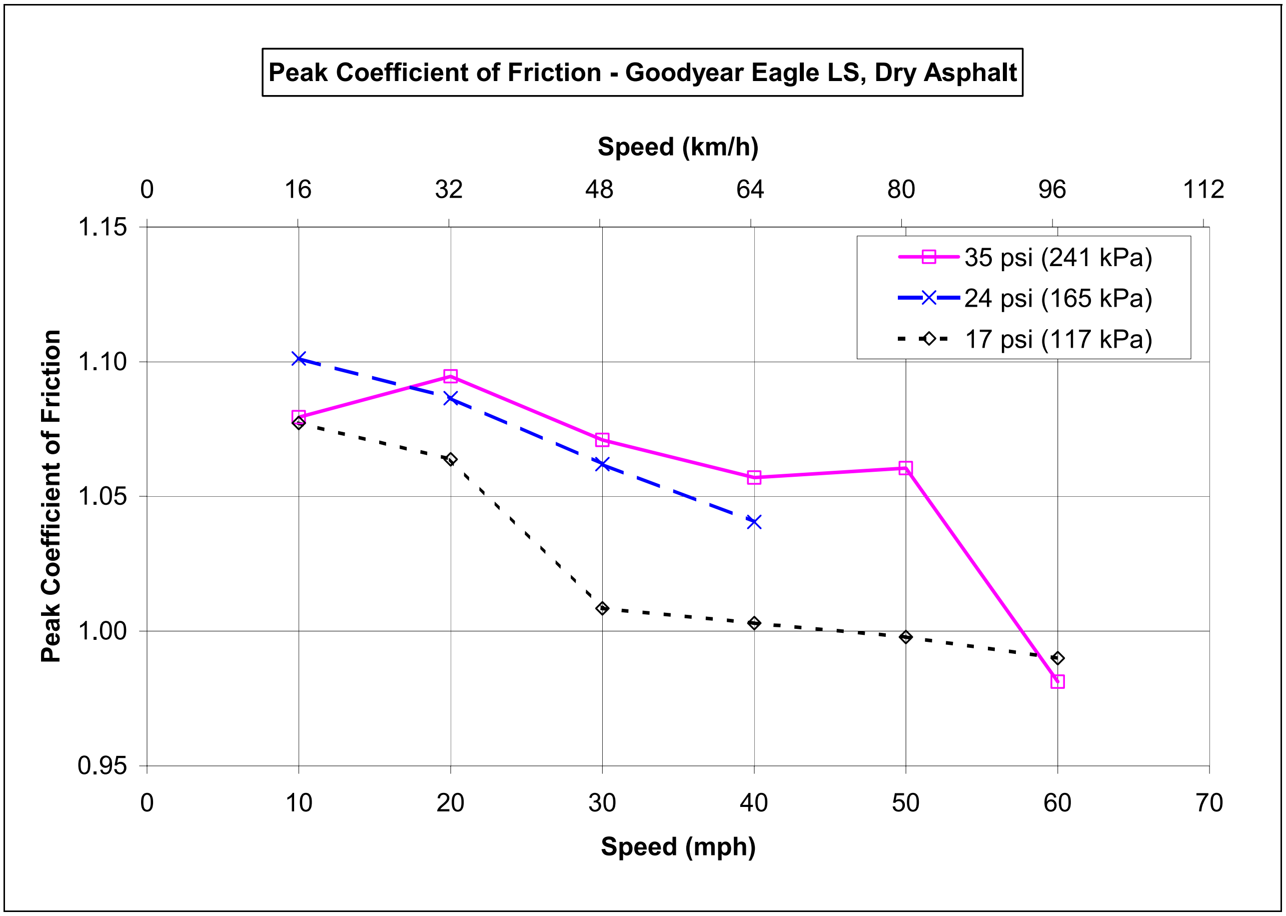

Figure 3.8: Eagle Tire - Dry Peak Friction Coefficients vs. Speed

Figure 3.8 displays the trends of the peak friction coefficient versus test speed as measured on dry asphalt with the Goodyear Eagle LS Tire. The x-axis features test speed with a scale that ranges from 0 to 70 mph (0 to 113 kph). The y-axis features peak coefficients of friction with a scale that ranges from 0.95 to 1.15. For 35 and 17 psi (241 and 117 kPa), the average values of the peak coefficients were measured at six test speeds, which ranged from 10 to 60 mph (16 to 97km/h) in 10 mph (16km/h) increments. The 24 psi (165 kPa) data was measured at four test speeds, which ranged from 10 to 40 mph (16 to 64 km/h) in 10 mph (16km/h) increments. The data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. With the exception of 10 mph (16 km/h), where the peak coefficient at 35 psi (241 kPa) was lower than the value at 24 psi (165 kPa), the average peak coefficient was *noticeably lower at the 17 psi (117 kPa) than at 24 and 35 psi (165 and 241 kPa). The numerical data for this figure is located in Table 3.4.*

None of the test sequences at different inflation pressures were able to make it to 70 mph due to excessive tire wear. For 20-50 mph (32-80 kph) speeds, on dry asphalt, the Eagle tires showed a decrease in their average peak coefficient of friction when the inflation pressure was halved. The decrease was typically in this range was about 5 percent. The dry peak coefficients were essentially unchanged at both 10 and 60 mph (16 and 97 kph). As Figure 3.8 shows, the change in the dry peak coefficient for this tire between 35 and 24 psi (241 and 165 kPa) was minimal.

Both the SRTT and Eagle tires showed similar trends in that the dry peak coefficients of friction decreased as the inflation pressure decreased. The SRTT tire was more sensitive to changes in inflation pressure and had a consistent response over the range of speeds. The Eagle tire was less sensitive to inflation pressure, perhaps because of its lower aspect ratio (60 compared to 75), and the response of the tire to decreases in inflation pressure was not nearly as consistent over the test speeds. The large amount of tread wear incurred during the dry peak testing, which caused the 24 psi (165 kPa) tests to be halted after just four of the seven speeds were completed, may have compromised the dry peak results at speeds above 40 mph (64 kph).

3.2 Slide Coefficient of Friction

Each slide number is also the average of five samples, with any outliers removed before averaging. Slide numbers are taken by maintaining a constant skid truck speed and locking test wheel five times in 1-3 second durations.

3.2.1 Wet Slide Coefficient of Friction

Wet slide tests, though harder on the tire than the wet peak tests, did not produce substantial tire wear. Therefore, all test speeds were completed without exceeding the tread wear limit.

Table 3.6: Wet Slide Coefficients of Friction from State Route OH 347

Tire / Inflation Pressure Tire		SRTT	SRTT	EAGLE	EAGLE	EAGLE
Speed (mph)	Speed (kph)	35 psi (241 kPa)	17 psi (117 kPa)	35 psi (241 kPa)	24 psi (165 kPa)	17 psi (117 kPa)
10	16	0.72	0.73	0.68	0.69	0.70
20	32	0.65	0.67	0.58	0.65	0.62
30	48	0.60	0.61	0.56	0.57	0.55
40	64	0.57	0.55	0.51	0.53	0.50
50	80	0.51	0.50	0.46	0.48	0.48
60	97	0.49	0.44	0.46	0.41	0.41
70	113	0.45	0.45	0.40	0.36	0.37

Table 3.7: Percent Change in the Wet Slide Coefficient of Friction between Pressures

Tire / Inflation Pressure		SRTT	EAGLE	EAGLE	EAGLE
Speed (mph)	Speed (kph)	35 / 17 psi (241 /117 kPa)	35 / 24 psi (241 / 165 kPa)	35 / 17 psi (241 / 117 kPa)	24 / 17 psi (165 / 117 kPa)
10	16	1.4%	1.5%	2.9%	1.5%
20	32	3.1%	12.1%	6.9%	-4.6%
30	48	1.7%	1.8%	-1.8%	-3.5%
40	64	-3.5%	3.9%	-2.0%	-5.7%
50	80	-2.0%	4.4%	4.4%	0.0%
60	97	-10.2%	-10.9%	-10.9%	0.0%
70	113	0.0%	-10.0%	-7.5%	2.8%
Average		-1.4%	0.4%	-1.1%	-1.4%
Standard Deviation		4.5%	8.2%	6.4%	3.2%

As seen in Table 3.7, Figure 3.9, and Figure 3.10, the effects of inflation pressure on the wet slide coefficients for the SRTT tire had mixed results.

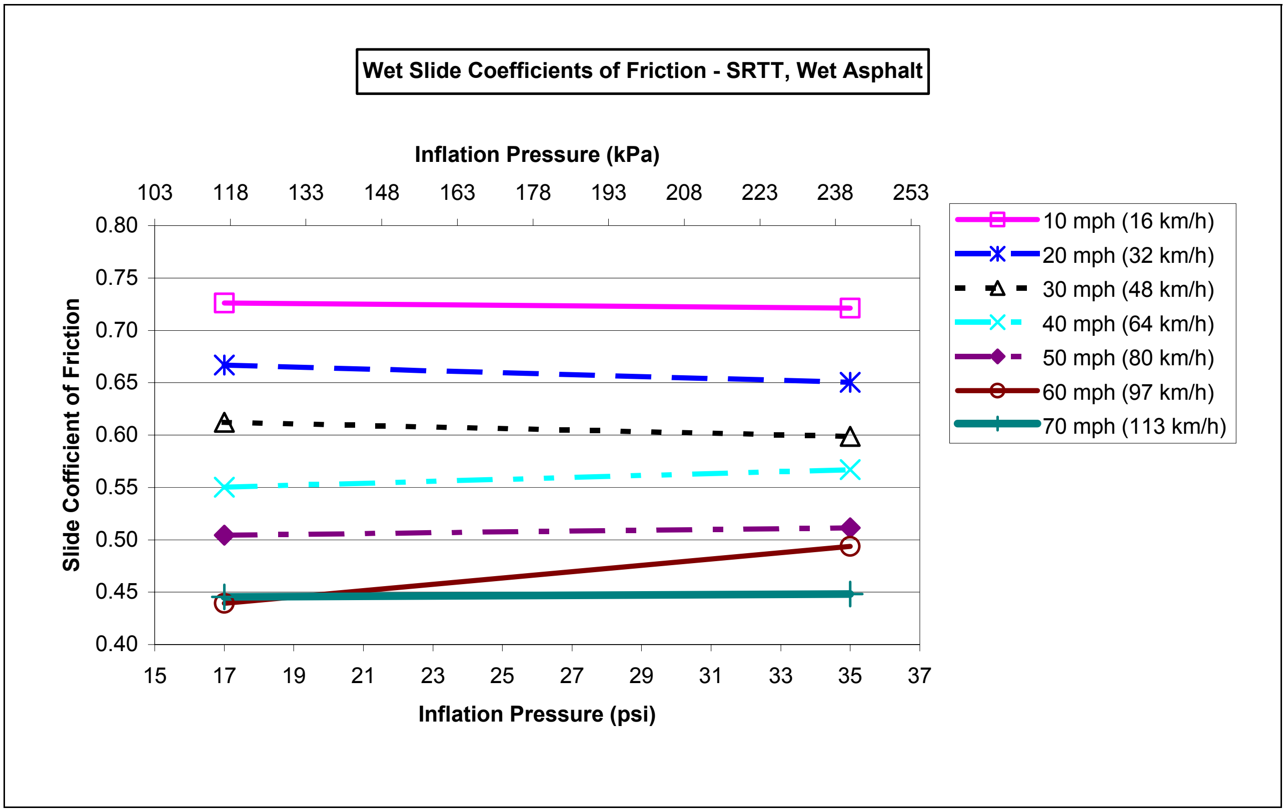

Figure 3.9: SRTT Tire - Wet Slide Friction Coefficients vs. Inflation Pressure

Figure 3.9 displays the trends of the slide friction coefficient versus inflation pressure as measured on wet asphalt with the SRTT Tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features slide coefficients of friction with a scale that ranges from 0.40 to 0.80. Average values of the slide coefficients were measured for two inflation pressures: 17 psi (117 kPa) and 35 psi (241 kPa). For each of the seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments, the two data points are connected by a line. With the exception of the 60 mph (97 km/h) test speed, which shows a marked decrease in the average slide coefficient as inflation pressure was dropped from 35 to 17 psi (241 to 117 kPa), the change in the slide coefficient is very slight for the other six speeds. At lower speeds, the slide coefficient slightly increased when the tire pressure was halved. At higher speeds, the slide coefficient slightly decreased when inflation pressure was halved. The numerical data for this figure is located in Table 3.6.

In the 10 to 30 mph (16 to 48 kph) range, the coefficients showed an average increase of 2% as inflation pressure was dropped from 35 psi (241 kPa) to 17 psi (117 kPa). In the 40 to 60 mph (64 to 97 kph) range, the coefficients showed an average decrease of about 5%. There was no measured effect at 70 mph (113 kph).

The effects of inflation pressure on the wet slide coefficient of friction are plotted against test speed for the SRTT tires in Figure 3.10.

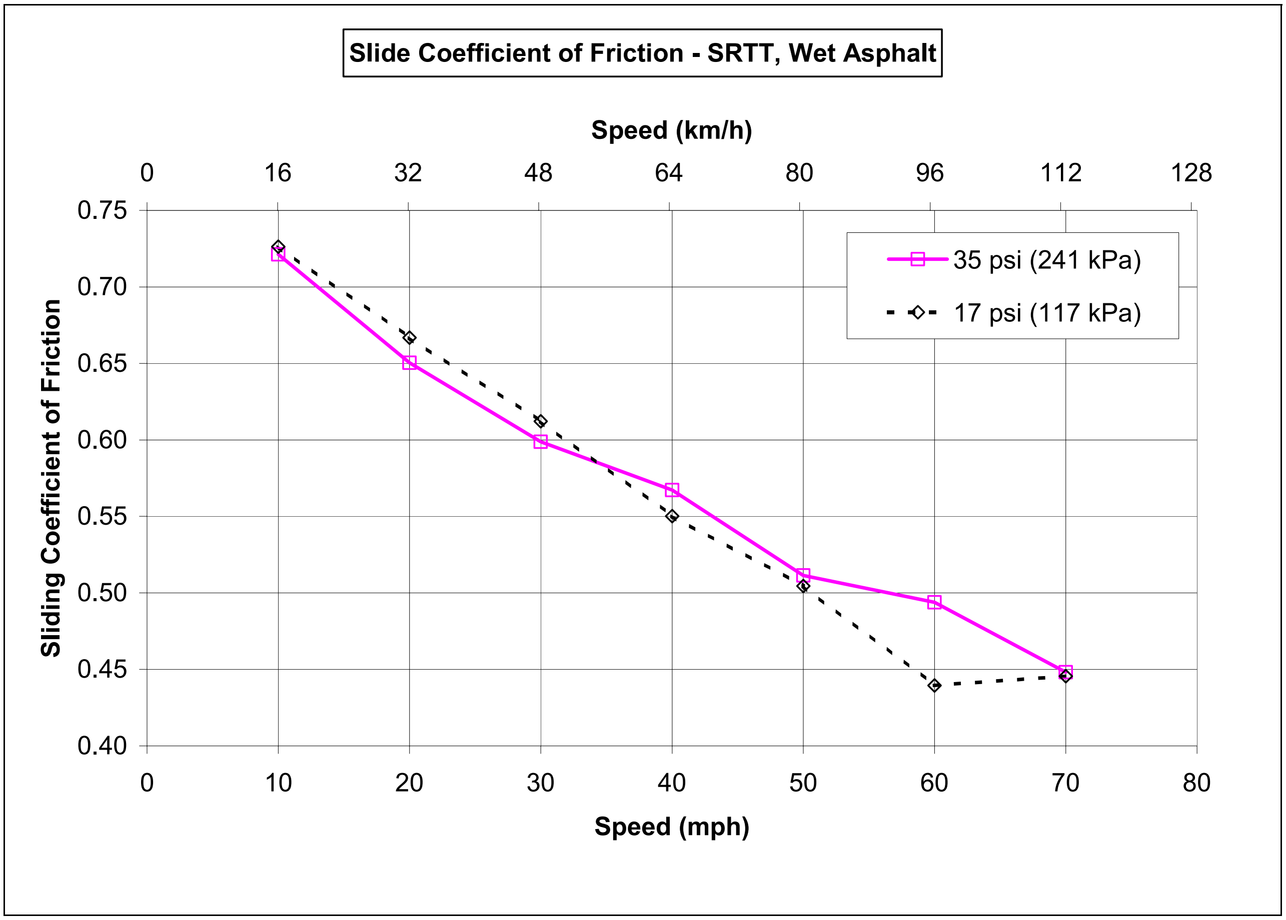

Figure 3.10: SRTT Tire - Wet Slide Friction Coefficients vs. Speed

Figure 3.10 displays the trends of the slide friction coefficient versus test speed as measured on wet asphalt with the SRTT Tire. The x-axis features test speed with a scale that ranges from 0 to 80 mph (0 to 129 kph). The y-axis features slide coefficients of friction with a scale that ranges from 0.40 to 0.75. Average values of the slide coefficients were measured at seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments. The seven data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. Over the range of seven speeds, both lines are virtually on top of each other, indicating that inflation pressure had little or no influence on the wet slide coefficients for this tire. The numerical data for this figure is located in Table 3.6.

Except for the 10.5 percent higher wet slide coefficient at 60 mph (97 kph), which was probably an outlier, the differences in the wet slide coefficients with the SRTT tire between 35 and 17 psi (241 and 117 kPa) average 1.4 percent and are thought to be less than the amount of measurement uncertainty. Overall, inflation pressure does not seem to have a substantial effect on the wet slide coefficient of the SRTT tire.

Plots of the wet slide coefficient data versus inflation pressure for the Eagle tire are shown in Figure 3.12.

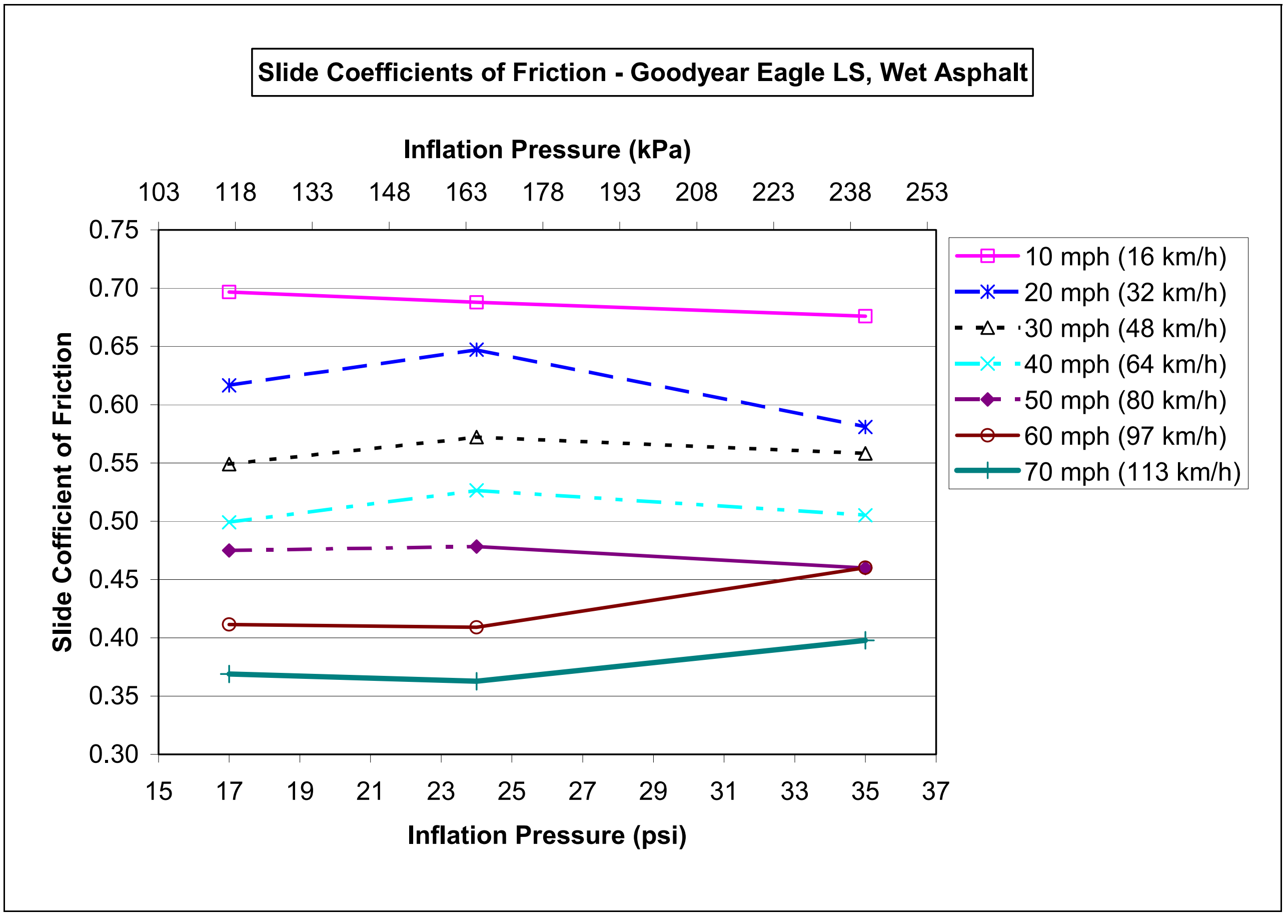

Figure 3.11: Eagle Tire - Wet Slide Friction Coefficients vs. Inflation Pressure

Figure 3.11 displays the trends of the slide friction coefficient versus inflation pressure as measured on wet asphalt with the Goodyear Eagle LS tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features slide coefficients of friction with a scale that ranges from 0.30 to 0.75. Average values of the slide coefficients were measured for three inflation pressures: 17 psi (117 kPa), 24 psi (165 kPa), and 35 psi (241 kPa). For each of the six test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments, the three data points are connected by an incremental point-by-point line. At low speeds, the wet slide coefficients initially increased as inflation pressure dropped from 35 to 24 psi (241 to 165 kPa), then decreased as inflation pressure dropped from 24 to 17 psi (165 to 117 kPa). At high speeds, the coefficients initially decreased *when inflation pressure dropped from 35 to 24 psi (241 to 165 kPa), then leveled off and did not change when inflation pressure dropped from 24 to 17 psi (165 to 117 kPa). Overall, the slopes of the lines are very shallow, meaning that the influence of inflation pressure is relatively small. The numerical data for this figure is located in Table 3.6.*

The wet slide coefficients are plotted against speed in Figure 3.12.

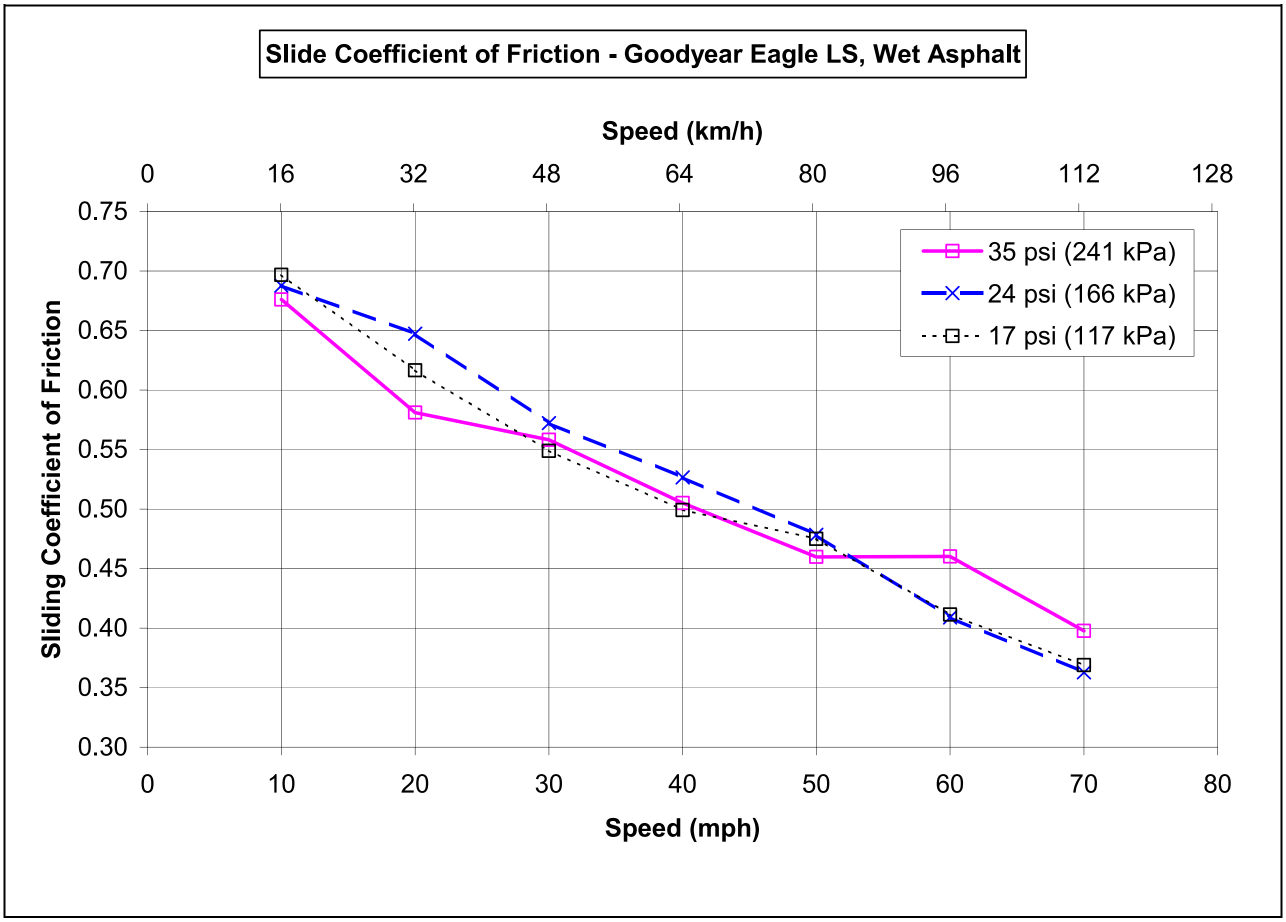

Figure 3.12: Eagle Tire - Wet Slide Friction Coefficients vs. Speed

Figure 3.12 displays the trends of the slide friction coefficient versus test speed as measured on wet asphalt with the Goodyear Eagle LS Tire. The x-axis features test speed with a scale that ranges from 0 to 80 mph (0 to 129 kph). The y-axis features slide coefficients of friction with a scale that ranges from 0.30 to 0.75. Average values of the slide coefficients were measured at seven test speeds, which ranged from 10 to 70 mph (16 to 113 km/h) in 10 mph (16km/h) increments. The seven data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. Over the range of seven speeds, the lines that represent the three pressures are close together and cross frequently, which indicates that inflation pressure had a small influence on the wet slide coefficients for this tire. The numerical data for this figure is located in Table 3.6.

At a speed of 60 mph (97 kph), the wet slide coefficient of friction for the Eagle tire is 10.9 percent higher at 35 than at 17 psi (241 than at 117 kPa). At a speed of 20 mph (32 kph), the wet slide coefficient is 6.9 percent lower at 35 than at 17 psi (241 than at 117 kPa). The wet slide coefficients at 35 psi (241 kPa) are lower from 10 to 50 mph (16 to 80 kph) than for the 24 and 17 psi pressures and higher at 60 and 70 mph (97 and 117 kph). The average difference between 35 and 17 psi (241 and 117 kPa) is a decrease of 1.1 percent. This level is difference is probably due to random measurement uncertainty. Overall, inflation pressure does not seem to have a substantial effect on the wet slide coefficient of the Eagle tire.

3.2.2 Dry Slide Coefficient of Friction

The cost and limited availability of the SRTT tires, which must be special ordered from the Uniroyal Goodrich Tire Company, meant that the supply of these tires was exhausted before the dry slide coefficient of friction tests could be completed. A few of the Eagle tires had sufficient tread for the dry tests, but were flat-spotted after the first 20 skids (each slide number at each speed is the average of 5 skids).

One particular problem with obtaining the dry slide coefficient (skid tests) for normal tires is that the tire has a tendency to "find" the flat spot from the previous test and rotate to this spot at the beginning of the skid. The tire wear produced is extremely localized and the tire tread is worn out much faster. In addition, the tread wear appeared to be more severe when the tires were tested while underinflated. We know that tire tread depth has a significant effect on the measured peak and slide coefficient of friction for a tire.[6] Therefore, the results of dry slides after the first four runs (above 40 mph) may be significantly affected by the induced flat-spotting of the tires.

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[6] Dry friction coefficients can increase by as much as 20% as tires go from a new tire's 9-11/32" tread depth to a worn 2/32" tread depth. Bosch Automotive Handbook, 4th Edition. Pg. 335, Table - "Adhesion to road surface".

Table 3.8: Dry Slide Coefficients of Friction from SR OH 347, 10-40 mph (16-64 kph)

Tire / Inflation Pressure		EAGLE	EAGLE	EAGLE
Speed (mph)	**Speed (kph)**	**35 psi (241 kPa)**	**24 psi (165 kPa)**	**17 psi (117 kPa)**
10**	**16**	0.83	0.79	0.77
20	**32**	0.80	0.73	0.73
30	**48**	0.78	0.76	0.75
40	**64**	0.78	0.81	0.80
50	*80*	*0.79*	*	*0.87*
60	*97*	*0.80*	*	*0.85*
70	*113*	*	*	*

*Test terminated when allowable tire wear was exceeded
**Speeds in bold were tested during the first 20 dry skids for each tire

Table 3.9: Percent Change in the Dry Slide Coefficient of Friction between Pressures

Tire / Inflation Pressure		EAGLE	EAGLE	EAGLE
Speed (mph)	**Speed (kph)**	**35 / 24 psi**	**35 / 17 psi**	**24 / 17 psi**
10**	**16**	-4.8%	-7.2%	-2.5%
20	**32**	-8.8%	-8.8%	0.0%
30	**48**	-2.6%	-3.9%	-1.3%
40	**64**	3.9%	2.6%	-1.2%
50	*80*	*	*10.1%*	*
60	*97*	*	*6.3%*	*
70	*113*	*	*	*
Average: 10-40mph (16-64 kph)		-3.1%	-4.3%	-1.3%
Standard Deviation		5.3%	5.0%	1.0%

*Test terminated when allowable tire wear was exceeded
**Speeds in bold were tested during the first 20 dry skids for each tire

The effects of inflation pressure on the dry slide coefficients for the Eagle tire are displayed in Figure 3.14. Again, above 40 mph (64 kph) there's a possibility that tread wear may have influenced the results.

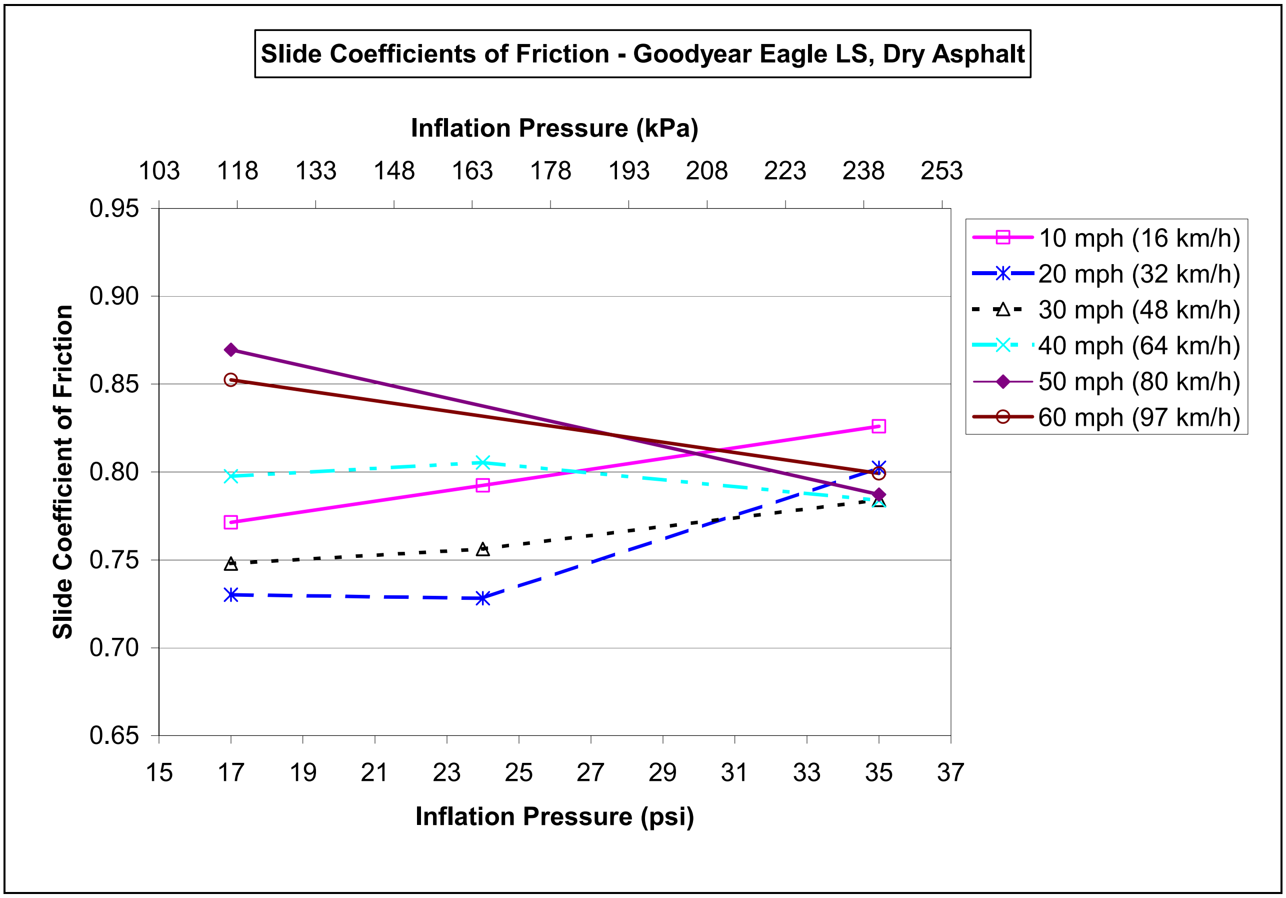


Figure 3.13: Eagle Tire - Dry Slide Friction Coefficients vs. Inflation Pressure

Figure 3.13 displays the trends of the slide friction coefficient versus inflation pressure as measured on dry asphalt with the Goodyear Eagle LS tires. The x-axis features inflation pressures with a scale that ranges from 15 to 37 psi (103 to 255 kPa). The y-axis features slide coefficients of friction with a scale that ranges from 0.65 to 0.95. For speeds of 10 to 40 mph (16 to 64 km/h), the average values of the slide coefficients were measured for three inflation pressures: 17 psi (117 kPa), 24 psi (165 kPa), and 35 psi (241 kPa). For 50 and 60 mph (80 and 97 Km/h), test at only two inflation pressures, 17 psi (117 kPa) and 35 psi (241 kPa), could be completed. For each of the six test speeds, which ranged from 10 to 60 mph (16 to 97 km/h) in 10 mph (16km/h) increments, the data points are connected by an incremental point-by-point line. At low speeds, the dry slide coefficients rapidly decreased as inflation pressure dropped from 35 to 24 psi (241 to 165 kPa), then leveled off from 24 to 17 psi (165 to 117 kPa). At 50 & 60 mph (80 an 90 km/h) the dry slide numbers sharply increase when tire pressure was halved. Data for the higher test speeds, especially the last two speeds, was probably compromised by significant tire wear. The numerical data for this figure is located in Table 3.8.

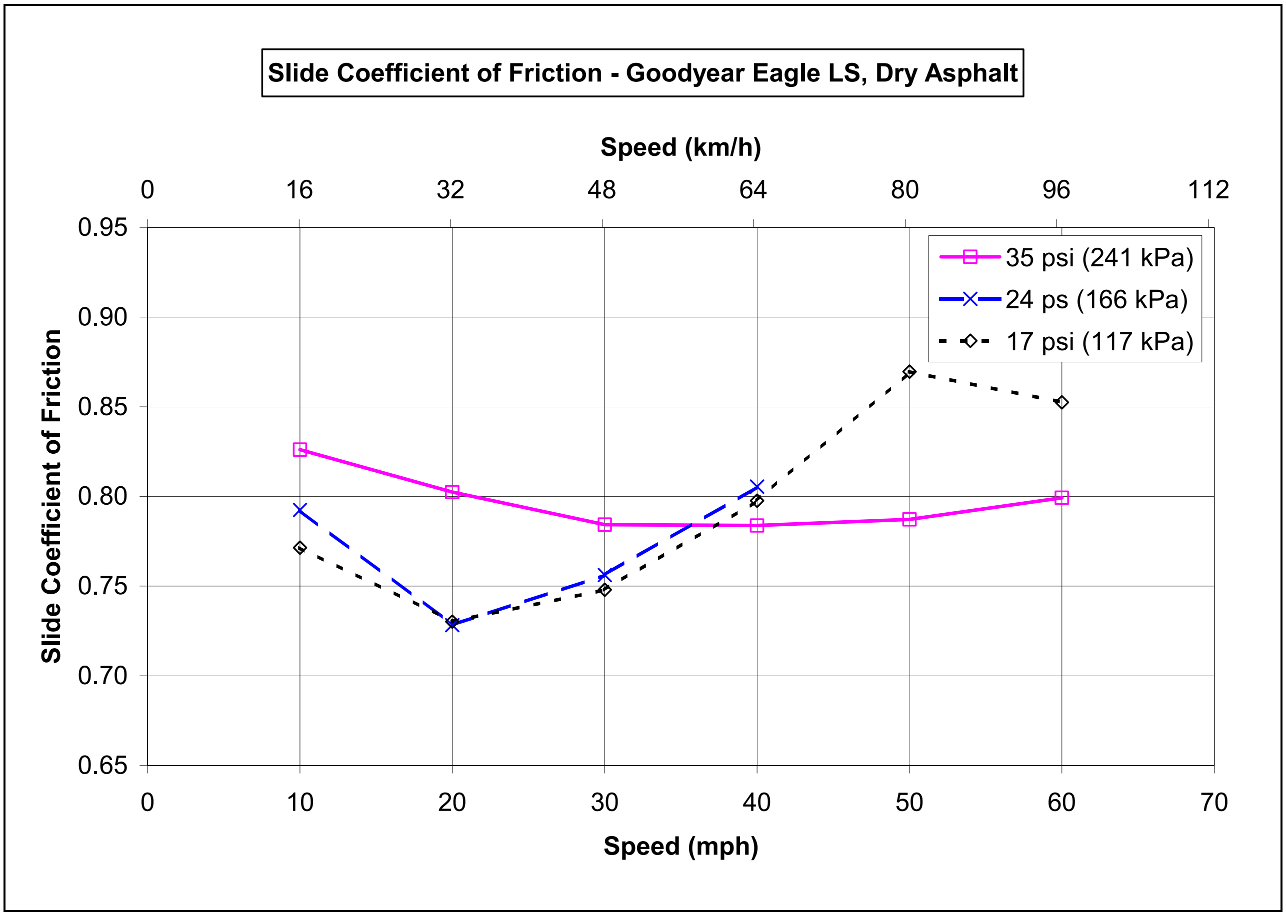


Figure 3.14: Eagle Tire - Dry Slide Friction Coefficients vs. Speed

Figure 3.14 displays the trends of the slide friction coefficient versus test speed as measured on dry asphalt with the Goodyear Eagle LS Tire. The x-axis features test speed with a scale that ranges from 0 to 70 mph (0 to 113 kph). The y-axis features slide coefficients of friction with a scale that ranges from 0.65 to 0.95. Average values of the slide coefficients were measured at seven test speeds, which ranged from 10 to 60 mph (16 to 97 km/h) in 10 mph (16km/h) increments. The six data points for each inflation pressure are connected by an incremental point-by-point line, rather than a curve fit. At speeds below 30 mph (48 km/h), the dry slide coefficients for the 17 and 24 psi (117 and 165 kPa) pressures were well below those for the 35 psi (241 kPa) pressure. Between 30 and 40 mph (48 and 64 km/h), the dry slide coefficients for the17 and 24 psi (117 and 165 kPa) pressures sharply increased and rose past the values for the 35 psi (241 kPa) pressure. The numerical data for this figure is located in Table 3.8.

At a speed of 10 mph (16 kph), the dry slide coefficient of friction of the Eagle tire is 7.2 percent higher at 35 than at 17 psi (241 than at 117 kPa). At a speed of 20 mph (32 kph), the dry slide coefficient is 8.8 percent higher at 35 than at 17 psi (241 than at 117 kPa). At this point the authors must caution the reader that significant tread wear was incurred during each dry slide tests. While the reversal of the trend beyond the first 10 skids (10 & 20 mph [16 & 32 kph]) may be the actual effect of speed on the dry slide coefficients, tread wear may have also significantly influenced these results. More testing using new (but broken in) tires for each test speed would be needed to fully evaluate the effects of inflation pressure on the dry slide coefficient.

4.0 COMPARISONS

The VRTC found two sources of data on the effects of inflation pressure on the peak and slide coefficients of friction to compare its results with. The first was a paper done by B.F. Goodrich Co. in 1980 [3]. The second was a series of tests done by Goodyear Tire & Rubber Company in 2001 following a notice of proposed rulemaking on tire pressure monitoring systems [4].

4.1 B.F. Goodrich Co.

In 1980, Collier and Warchol of the B.F. Goodrich Co. published a paper that contained results on the effects of inflation pressure on radial tire performance [3]. Among these results were the effects of inflation pressure on wet and dry coefficients of friction. Their dry tests were conducted on an asphalt surface with a 0.81 dry skid number (State Route 347, the VRTC test surface, had a 0.83 dry skid number). They used a tire load of 85% of the T&RA design load for each pressure (VRTC used 75% of design load for the 35 psi (241 kPa) max inflation pressure of the Eagle LS and used the ASTM E 1337 specified load for the SRTT tire).

Collier and Warchol found that at 40 mph (64 kph) the dry peak coefficient of friction for their radial test tire increased slightly as the inflation pressure increased from 16 to 48 psi (110 to 330 kPa). They also found that the dry slide coefficient stayed relatively constant as inflation pressure rose from 16 to 32 psi (110 to 220 kPa) and then dropped off from 32 to 48 psi (220 to 330 kPa).

The results of the dry peak and slide tests run by the VRTC at 40 mph (64 kph) on dry asphalt are displayed in Figure 4.1.

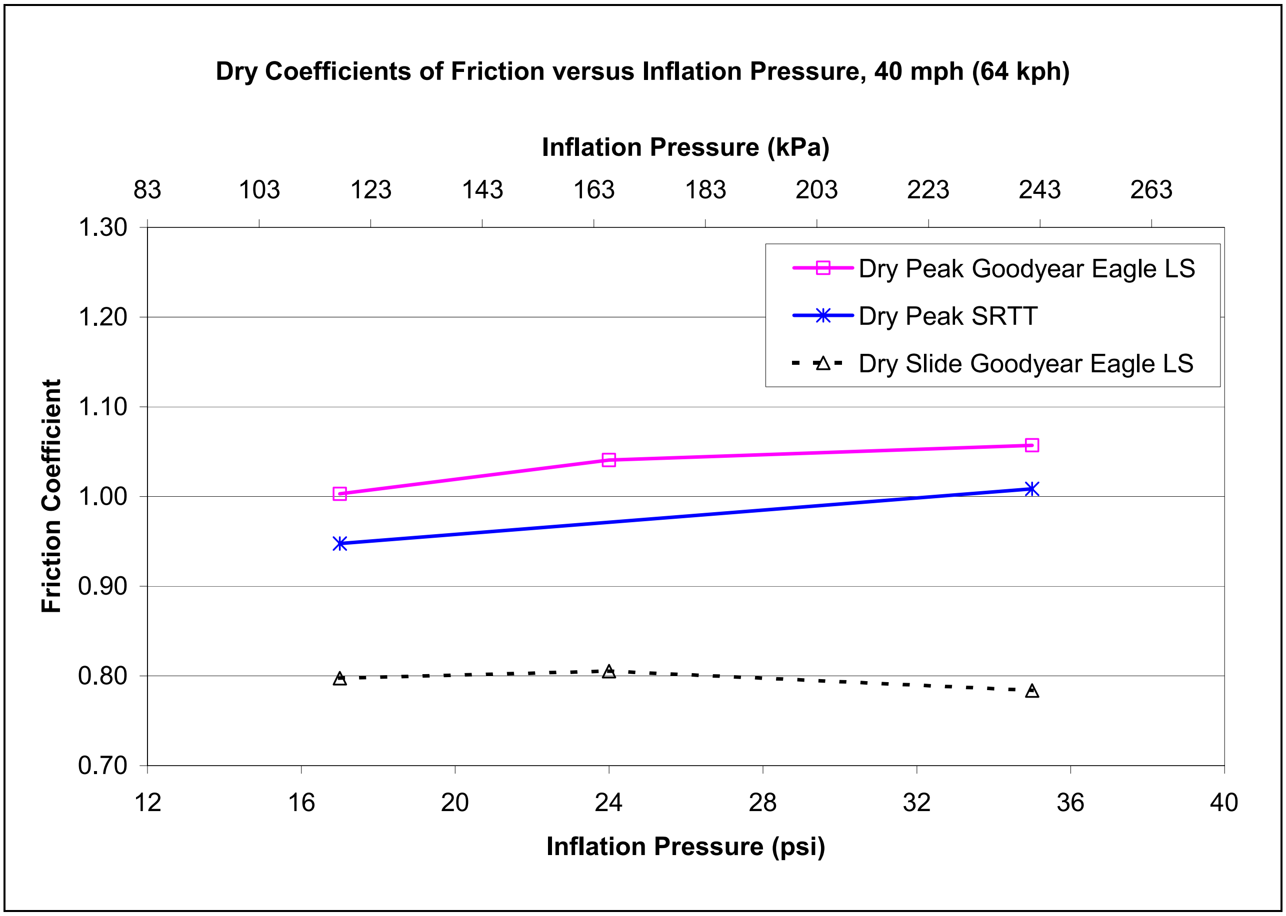


Figure 4.1: Results of Peak and Slide Tests on Dry Asphalt (State Route 347)

Figure 4.1 displays the results of dry peak and dry slide friction tests with the Goodyear Eagle LS Tire as well as dry peak friction tests with the SRTT Tire on dry asphalt. The x-axis features inflation pressures with a scale that ranges from 12 to 40 psi (83 to 276 kPa). The y-axis features slide coefficients of friction with a scale that ranges from 0.70 to 1.30. The results were the average value of friction numbers taken at three inflation pressures: 17 psi (117 kPa), 24 psi (165 kPa), and 35 psi (241 kPa). The average dry peak coefficients for the Eagle and SRTT Tires rose as inflation pressure was increased. The average dry slide coefficient for the Eagle Tire was the same at 17 and 24 psi (117 and 165 kPa) and decreased slightly at 35 psi (241 kPa).

The same trends from Collier and Warchol's data are seen in the VRTC data. The dry peak coefficients for the Eagle and SRTT tires rise slightly for increasing inflation pressure. Also similar were the dry slide coefficients for the Eagle tires (the SRTT tires were used up before dry slide tests), which were relatively constant in the 16-24 psi (110-165 kPa) range and dropped off in the 24 to 36 psi range (more data points are needed to quantify these ranges). This correlation of data suggests that the trends observed in the VRTC's testing may be representative of radial tire behavior on dry asphalt.

The wet peak and slide tests conducted by Collier and Warchol were done on wet polished concrete (dry slide of 0.30) and cannot be directly compared with the VRTC data on wet asphalt (dry slide of 0.55 to 0.63). Collier and Warchol observed that the wet peak and slide coefficients "generally remain constant or increase slightly with higher inflation pressure for all three tire constructions, at all three speeds." The wet peak coefficients Eagle tires (Figure 3.3) have an opposite trend from Collier and Warchol's findings and moderately decrease as inflation pressure increases. However the 1980's era SRTT tire followed the same trend and had a wet peak coefficient that increased with higher inflation pressure. The wet slide coefficients for both tires, as seen in Figure 3.9 and Figure 3.11, agreed with Collier and Warchol's findings and in general did not change with inflation pressure.

4.2 Goodyear Tire & Rubber Company

On September 14, 2001 the Goodyear Tire and & Rubber Company submitted data to NHTSA on the effects of inflation pressure on the peak and slide coefficients of friction as well as on vehicle stopping distances in both wet and dry wet and dry conditions. Their tests included dry testing as well as two water depths, one passenger car and one light truck tire, and two vehicles with ABS on and off for the stopping distance results. A comparison of the Goodyear test surface to the VRTC test surface follows:

Table 4.1: Surface Comparison between Goodyear Test Surface and SR 347

Test Surface	Wet Peak	Wet Slide	Dry Peak	Dry Slide
Goodyear Test Facility	0.89	0.46	0.96	0.72
SR 347 – 7 Year Old Asphalt*	0.87	0.63	1.01	0.83

*Tests completed by the VRTC

Goodyear tested two P-Metric passenger car tires, one typically used on passenger cars (Integrity) and one typically used on light trucks (Wrangler RT/S).

Table 4.2: Goodyear and VRTC Test Tires Size, Type, and Test Load

Tire	Size	Type	Test Load
Goodyear Integrity	P215/70 R15	Radial	1080 lbf (4804 N)
Goodyear Wrangler RT/S	P235/75 R15	Radial	1490 lbf (6628 N)
ASTM E 1136 (SRTT)*	P195/75 R14	Radial	1031 lbf (4586 N)
Goodyear Eagle LS*	P225/60 R16	Radial	1205 lbf (5360 N)

*Tests completed by the VRTC

Graphs of Goodyear friction coefficient data for the Integrity and Wrangler tires with the corresponding VRTC Eagle tire data can be found in Appendix 1. This appendix only contains an analysis of the dry and 0.020” (0.51mm) water depth Goodyear data. Excluded was the data from Goodyear’s tests with 0.050” (1.27mm) water depth, since this depth approximately twice the depth of water used by VRTC for testing.

Goodyear found that at 20, 40, and 60 mph (32, 64, and 97 kph), the wet peak coefficients for the Integrity and Wrangler tires decreased uniformly as inflation pressure dropped (Appendix 1). These results agree with the VRTC’s tests of the SRTT tire (only tested at 17 & 35 psi [241 kPa]). However, the VRTC tests with the Eagle tire had an opposite trend. For the Eagle tire the wet peak friction was higher for five of the seven tests speeds at the lower inflation pressures.

Goodyear’s dry peak results for both the Integrity and Wrangler tires were mixed, with the dry peak coefficients sometimes increasing and sometimes decreasing with inflation pressure. The trends seem to display large speed dependency. Results from VRTC tests of the SRTT tire followed a clear trend of decreased dry peak coefficients at lower inflation pressures for all seven speeds. VRTC’s dry peak coefficients for the Eagle tires were similar to Goodyear’ results, showing mixed trends that varied with speed.

Goodyear’s wet slide coefficients for both the Integrity and Wrangler follow a clear trend of decreasing as inflation pressure drops at all speeds. VRTC wet slide tests of the SRTT and Eagle tires yielded results that showed little or no effect of inflation pressure at approximately the same water depth.

Dry slide results for the both the Goodyear and VRTC tests were mixed, with the trends of the coefficients varying significantly with speed.

4.3 Comparison Summary

The results from VRTC's dry peak (Eagle & SRTT tires) and slide tests (Eagle tires) at 40 mph (64 kph) closely mimicked the results on dry asphalt observed by Collier and Warchol in 1980 (B.F. Goodrich). While the wet peak and slide results with the Eagle tire on wet asphalt did not follow those observed by Collier and Warchol on wet polished concrete, the wet peak results with the SRTT tire did.

While the Goodyear and VRTC data suggests that inflation pressure seems to have an influence on wet peak friction coefficients, the trends appear to vary from tire to tire. The Integrity, Wrangler, and SRTT tires all had lower wet peak coefficients at reduced inflation pressures. The Eagle tire showed an opposite trend. While underinflation caused the wet slide coefficients to decrease for the Integrity and Wrangler tires, no appreciable change was witnessed for the Eagle or SRTT tires. The disagreement of the wet results may stem from inherent differences in the test tires, or perhaps water application methods.

The water depth of the VRTC tests was estimated to be approximately 0.01 to 0.02 inches (0.25 to 0.51mm). The actual depth is unknown since no means of accurately measuring the water depth on the crowned surface of SR 347 was available at the time of testing. Since the skid trailer's water application nozzles were too narrow to accommodate the wide Eagle LS test tires, the VRTC was forced to use a sprinkler truck to spray water onto SR 347. If Goodyear's facility has a built in watering system that measures and maintains the water depth, the authors feel that the Goodyear wet results may be more accurate than ones taken with the sprinkler truck water application. Further testing would be necessary to determine whether the discrepancy between the wet Goodyear and VRTC results were tire dependent or resulted from differences in test methodology.

With the exception of the dry peak results for the SRTT tire (80's era tire), the dry peak and slide coefficients for the other three tires showed mixed trends that were highly dependent on test speed. In general, on dry asphalt, the influence of underinflation was to reduce the peak and slide coefficients at low speeds and elevate peak and slide coefficients at high speeds.

5.0 <u>CONCLUSIONS</u>

As expected, and is well supported by literature, the general trend of the peak and slide coefficients was to decrease as test speed increased. The influence of inflation pressure on the peak and slide coefficients was dependent on the tire model and test conditions. Sensitivity to inflation pressure was clearly observable in some test conditions and yet in other conditions showed no influence.

Though the 35 verses 17 psi (241 verses 117 kPa) results show an overall general influence of inflation pressure, especially for the peak coefficients, the 35 verses 24 psi (241 verses 165 kPa) comparison is probably more indicative of a real world incident of tire underinflation. In that context, the 35-24 psi (241-117 kPa) results, which represent a 31% decrease in inflation pressure for the Eagle tires, were small and quite varied. Overall, the influence of inflation pressure on the friction coefficients varied with tire type, tire wear, test method, test speed, and surface conditions. The results for each test scenario are summarized in Table 5.1.

Table 5.1: Summary of Friction Trends as Inflation Pressure Dropped from 35 psi (241 kPa)

Coefficient	**Tire**	**35 to 24 psi (241 to 165 kPa)**	**35 to 17 psi (241 to 117 kPa)**
Wet Peak	SRTT	N/A	6.1 percent decrease
Wet Peak	EAGLE	3.2 percent <u>increase</u>	3.6 percent <u>increase</u>
Dry Peak	SRTT	N/A	6.9 percent decrease
Dry Peak	EAGLE	Tire inflation pressure had little or no effect	3.1 percent decrease
Wet Slide	SRTT	N/A	Tire inflation pressure had little or no effect
Wet Slide	EAGLE	Mixed, trends showed speed dependence	Tire inflation pressure had little or no effect
Dry Slide	EAGLE	3.1 percent decrease	Mixed, trends showed speed dependence

The wet and dry peak coefficients of friction decreased for the SRTT tire as inflation pressure decreased. While the dry peak coefficients for the Eagle tire also decreased as inflation pressure decreased, the wet peak coefficients actually increased as inflation pressure dropped. It is possible that at the minimal water depth for the wet tests, approximated 0.01 to 0.02” (0.25 to

0.51mm), the contact patch for this particular tire was more optimal at 24 or 17 psi (165 or 117 kPa) than at 35 psi (241 kPa). This would lead to the higher wet peak coefficients at the underinflated pressures. However, tire hydroplaning literature strongly suggests that at deeper water depths, the shape of an underinflated tire's contact patch is more apt to trap water under it and greatly reduce wet traction when compared to properly inflated tires. More testing, which perhaps includes deeper water depths, is necessary before reaching a conclusion on the wet peak results.

The wet slide coefficients did not seem to be sensitive to inflation pressure for either the SRTT or Eagle tires. Since the wet peak and slide tests only result in minor tread wear, these results are most likely accurate over the entire speed range.

The supply of SRTT tires was exhausted before dry slide tests could be completed on them. The Eagle tire yielded mixed results for the dry slide numbers. Excessive tire wear may have changed the tire-roadway interaction by the time the 20th skid was reached (past 40 mph [64 kph]). Tread depth appears to have a strong influence on the measured coefficients, and may have significantly influenced the dry slide results. Due to the considerable tread wear incurred during dry slide tests, a new tire for each test speed is recommended for future dry slide tests.

Tread wear should not have been an issue for the wet peak and slide coefficients, so the tires' rubber compounding, tread designs, and construction may account for the different results yielded with the SRTT and Eagle tires. Though both tires are of radial construction, the SRTT is an old design first specified by ASTM in 1986. The tire rubber compounding used in the SRTT tire may not represent current day compounding. The SRTT tire is a relatively narrow, soft-walled tire when compared to the high-performance Eagle touring radial with its stiff sidewalls. The Eagle tire was much wider at 225 mm than the SRTT at 195 mm. Also, the 60 series aspect ratio of the Eagle tire, compared to the 75 series of the SRTT, means that the Eagle tire had a lower profile sidewall. Since the primary factor in reducing the friction coefficients is a loss of contact patch area, which results from an inward cupping of the tire from underinflation (instead of the flat surface presented by a properly inflated tire), these tires may respond differently to underinflation.

Since brand new tires could not be used for each test condition in the matrix, tread wear may have affected the results. Therefore, these findings are preliminary and warrant a more thorough and comprehensive investigation.

Future testing of this type would be improved by adopting the following:

- A new set of tires should be used for each test condition to eliminate the effects of tread wear.
- Tires should be shaved to the average road-going tread depth to better approximate real-world conditions.
- The order of the test speeds should be randomized to help reduce the bias of the changing surface conditions with temperature.
- Radial tires of different sizes and brands should be tested to have a more representative sample of modern tires.
- Multiple water levels should be used and a repeatable method of monitoring the water depth should be applied.

Additional ASTM test procedures that may be useful guidelines for future work are listed in Appendix 2.

REFERENCES

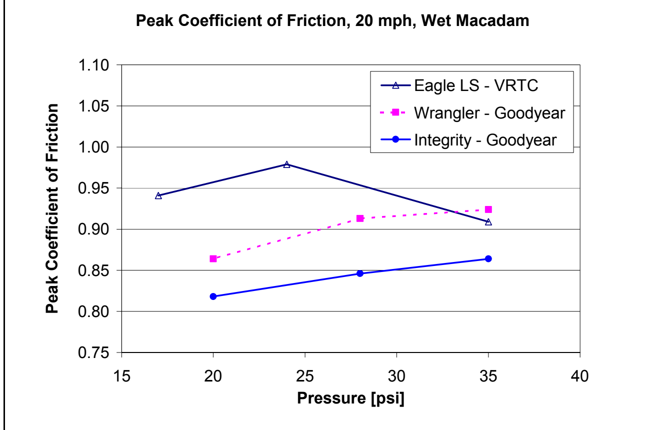
1. MacIsaac Jr., J.D., and Garrott, W.R., "*Stopping Distance vs. Tire Inflation Pressure"*, DOT Docket, Document NHTSA-2000-8572-70.

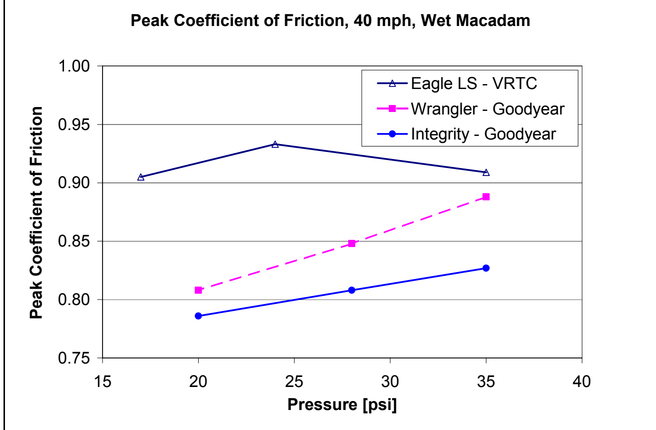
2. Robert Bosch GmbH, ***Bosch Automotive Handbook***, 4th Edition, 1996 p. 335 "Adhesion to road surface - Coefficients of static friction for pneumatic tires on various surfaces."

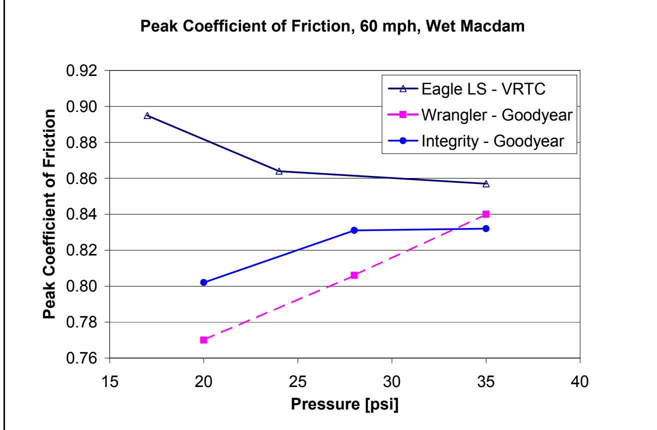
3. Collier, B.L., and Warchol, J.T., "The Effect of Inflation Pressure on Bias, Bias-Belted and Radial Tire Performance", SAE Paper # 800087, 1980.

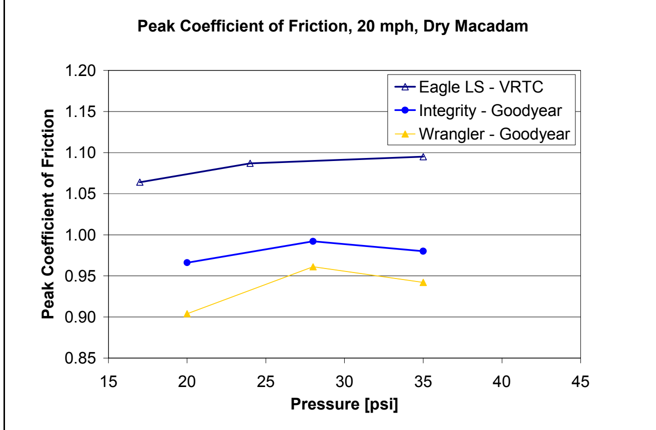
4. Goodyear Tire & Rubber Company, DOT Docket #: NHTSA-2000-8572-160, "Goodyear Tire & Rubber Company - Response to August 14 Memorandum re: Issues Relating To Tire Stopping Distance Testing"

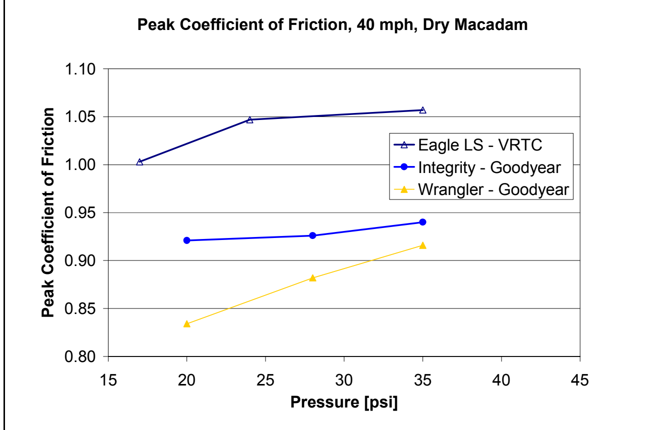
Appendix 1. Graphical Comparison of VRTC to Goodyear Friction Data

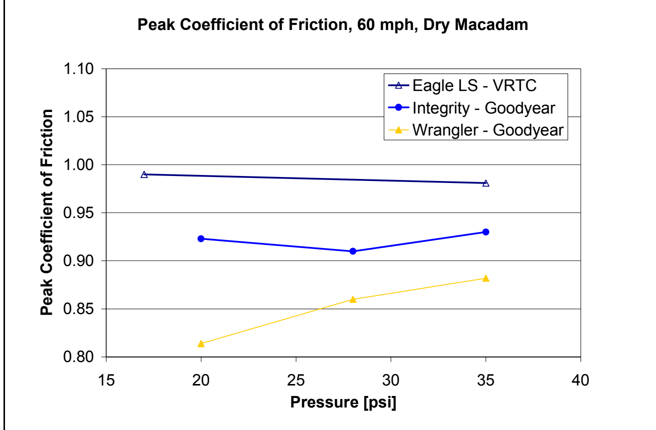


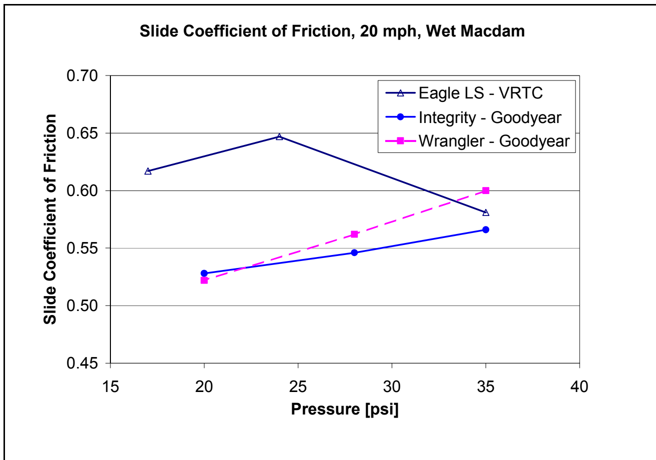


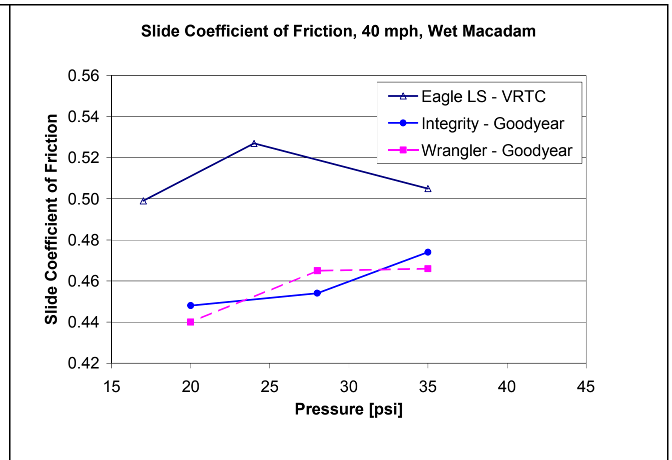


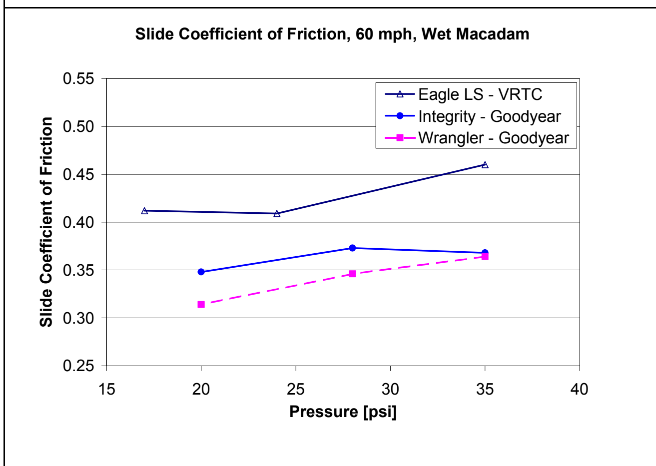


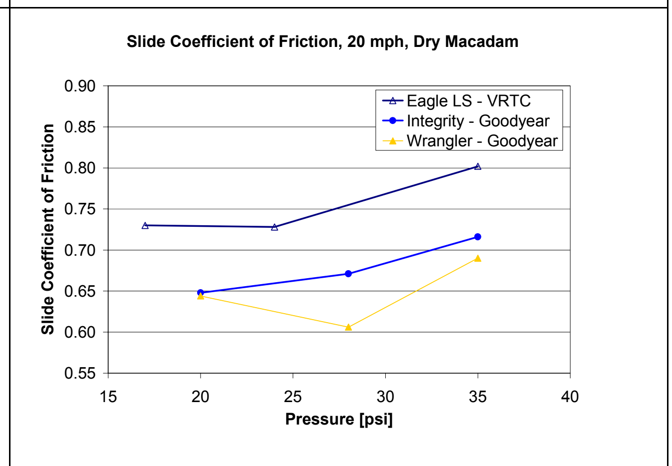


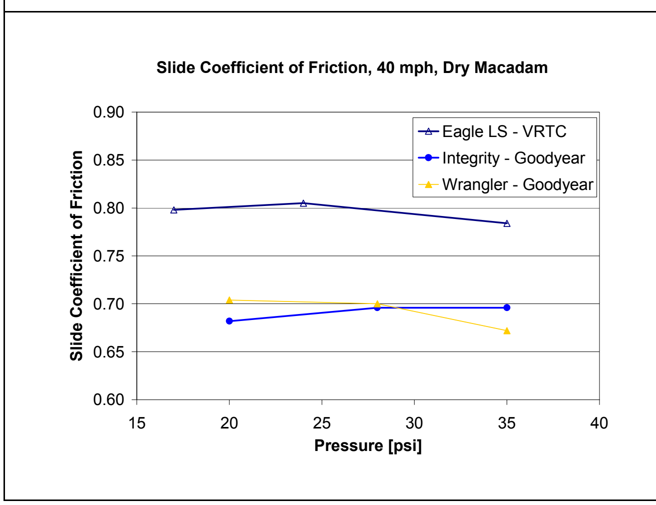


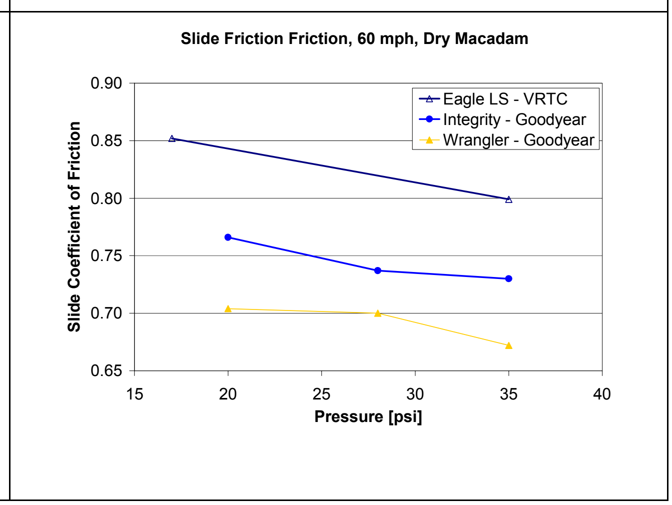












The twelve small graphs in Appendix 1 were added for comparison purposes and do not contain any new test data that was not discussed in the main body of this report.

Appendix 2. Alternate Tire Tests

Tests in addition to the ASTM E 274 and E 1337 tests might include:

ASTM F408-99	Test Method F408-99 Standard Test Method for Tires for Wet Traction in Straight-Ahead Braking, Using a Towed Trailer
ASTM F1572-99	Test Method F1572-99 Standard Test Methods for Tire Performance Testing on Snow and Ice Surfaces
ASTM F1649-96e1	Test Method F1649-96e1 Standard Test Methods for Evaluating Wet Braking Traction Performance of Passenger Car Tires on Vehicles Equipped with Anti-Lock Braking Systems
E445/E445M-88	Test Method E445/E445M-88(1996) Standard Test Method for Stopping Distance on Paved Surfaces Using a Passenger Vehicle Equipped With Full-Scale Tires